Using market research methodologies to advance public engagement with emerging climate technologies

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Abstract

The world is facing an unprecedented climate emergency that threatens humanity and global ecosystems. To help avoid some of the worst impacts, scientists are developing innovative technologies for addressing rising greenhouse gas emissions and climate change. However, in the early stages of research and development, the effectiveness, consequences, and desirability of implementing these technologies remains highly uncertain. Early public engagement is therefore critical for ensuring research and development pathways are acceptable to society. Currently, it remains unclear how best to engage the public on a global scale; an issue addressed in this thesis by drawing on theories and methodologies applied in the marketing discipline to advance the field of public engagement. The core methodology draws on marketing theories and measurement metrics by drawing on *associative network theories of memory* (ANTM) to model cognitive associations (i.e., public perceptions) with unfamiliar concepts.

Study One is a replication and extension of work by (Wright, Teagle, & Feetham, 2014) and uses qualitative and quantitative methods to measure public perceptions of six climate engineering technologies across countries and over time. The results show strong perceptual differences between technologies, but remarkable consistency between countries and over time. This consistency validates the cognitive association method as a robust tool for rapid public engagement and tracking perceptions as they evolve.

Study Two builds on Study One by drawing on additional *dual processing theories* and using an experimental design to test how citizens form opinions about emerging climate technologies. Contrary to concerns that survey methods elicit insufficiently considered responses, the study finds that citizens rely on rapid, snap judgements to form opinions, and that encouraging more thorough consideration does not affect their responses. Thus, the research further validates the use of survey methodologies for public engagement.

Study Three shifts focus, measuring perceptions of alternative fuels for decarbonising the shipping industry – a previously unresearched topic. The study is also the first to use a mixed-method approach to modelling cognitive associations in academic literature. Again, the quantitative findings showed strong, previously-unknown differences in perceptions between alternative fuels. Furthermore, the qualitative analysis supplemented these findings with rich insights into the drivers behind differing public perceptions.

This thesis makes several notable contributions: Practically, the results demonstrate the public's consistent preference for Carbon Dioxide Removal over Solar Radiation Management, their cautious support for carbon capture technologies, a strong distaste for stratospheric aerosol injection and ammonia as a shipping fuel, a striking preference for nuclear propulsion over heavy fuel oil, support for hydrogen and biofuel powered shipping, support for local implementation of alternative shipping fuels, and conditional support for small-scale research into acceptable emerging technologies. Theoretically, the research advances ANTM and dual processing theories in the context of emerging technologies, yielding results that are broadly applicable to not only public engagement with science, but also market research, brand tracking, and consumer judgement. Methodologically, the research validates cognitive association methods for cross-country public engagement, demonstrates the ability to track perceptions over time, and demonstrates a mixed-method approach to modelling cognitive associations. Finally, the research demonstrates the importance of conducting early and ongoing public engagement to identify acceptable decarbonisation pathways, guide research trajectories, and inform climate policy.

Acknowledgements

To my supervisors Dr Pam Feetham and Prof. Malcolm Wright. I certainly never imagined completing a PhD. Now, nearly five years later, what started as a straightforward Master's project has evolved into a substantial PhD thesis, multiple journal articles, (virtual) conference presentations, and countless questions from friends and family asking "so what was it you were studying again?". Looking back at some of my early *rough* drafts, it is abundantly clear that my skills as a researcher have come a long way, and for that I am incredibly grateful.

Pam, in particular, I want to thank you for never being too busy to bounce ideas off and for talking me through more PhD-related crises than I care to remember. Likewise, Malcolm, I want to thank you for your impromptu mini statistics courses and your uncanny ability to find the perfect words to hammer a point home. I also wish to thank our co-author Prof. Damon Teagle for his conceptual and scientific contributions to our research. All of you have supported me throughout this journey and made it an ultimately rewarding experience.

To my parents Sue and Pete, my brothers Nicky and Adam, my friends, and colleagues, thank you for your ongoing support and (mostly) welcome distractions throughout this journey. If any of you ask again what my PhD was about, you can now expect me to respond with a rather large book.

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List of acronyms

Table 1: List of acronyms

Acronym	Meaning
ANTM	Associative Network Theories of Memory
AU	Australia
AUSD	Australian Dollars
BECCS	Bioenergy With Carbon Capture and Storage
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CO_2	Carbon Dioxide
COP	Conference of Parties
DACCS	Direct Air Capture and Carbon Storage
EW	Enhanced Weathering
GBP	British Pound Sterling
GeoMIP	Geoengineering Model Inter-comparison Project
GHG	Greenhouse Gas
GMO	Genetically Modified Organism
HFO	Heavy Fuel Oil
IMO	International Maritime Organisation
IPCC	International Panel on Climate Change
LNG	Liquid Natural Gas
MCB	Marine Cloud Brightening
MIS	Mirrors In Space
NAS	National Academy of Sciences
NEP	New Ecological Paradigm
NET	Negative Emissions Technologies
NIMBY	Not In My Backyard
NZ	New Zealand
NZD	New Zealand Dollars
RQ	Research Question
SAI	Stratospheric Aerosol Injection
SCoPEx	Stratospheric Controlled Perturbation Experiment
SD	Standard Deviation
SE	Standard Error
SPICE	Stratospheric Particle Injection for Climate Engineering
SRM	Solar Radiation Management
UK	United Kingdom
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US/USA	United States of America
USD	United States Dollar
YIMBY	Yes, In My Backyard

List publications

Table 2: List of publications

Publication	*Title · Author List · Journal Details*
Publication One Chapter 2.0 (Published 2020)	**The public remain uninformed and wary of climate engineering** Carlisle, D. P.*, Feetham, P. M., Wright, M. J., & Teagle, D. A. H. *Climatic Change*, Volume 160, Issue 2, Pages 303-322. https://doi.org/10.1007/s10584-020-02706-5 Impact Factor: 4.743
Publication Two Chapter 3.0 (Published 2021)	**Public engagement with emerging technologies: Does reflective thinking affect survey responses?** Carlisle, D. P*., Feetham, P. M., Wright, M. J., & Teagle, D. A. H. *Public Understanding of Science*, Online First. https://doi.org/10.1177/09636625211029438 Impact Factor: 2.976
Publication Three Chapter 4.0 (Submitted to journal)	**Public response to decarbonisation through alternative shipping fuels** Carlisle, D. P.*, Feetham, P. M., Wright, M. J., & Teagle, D. A. H.

**In all three publications, DC led the research design, fieldwork, analysis, and drafting of the publication.*

GENERAL INTRODUCTION

1.0 General introduction

This chapter begins with a brief introduction discussing why public engagement with emerging technologies is crucial for finding acceptable solutions to global issues and identifies the limitations of current methods. Next, the discussion identifies how marketing theory and market research techniques can help advance the public engagement discipline; thereby forming the basis of this research. The chapter then outlines the three studies contained in this thesis that advance public engagement with emerging climate technologies by using marketing theory and market research techniques. Lastly, the chapter provides an overview of how the thesis contributes to public engagement and marketing disciplines and outlines the structure of the remaining chapters.

1.1. Public engagement with emerging science

Public engagement is increasingly recognised as a core component of responsible innovation (Stilgoe, Lock, & Wilsdon, 2014). Despite the countless benefits to humanity, rapid advances in science have led to many instances where wider impacts are later found to be undesirable, dangerous, or unacceptable to society (e.g., the European Union moratorium on genetically modified organisms or New Zealand's anti-nuclear stance). Recognising the shortcomings of traditional risk-based assessments in predicting these unforeseen impacts, scholars have issued calls for a more anticipatory, reflexive, inclusive, and responsive framework for responsible innovation (Stilgoe, Owen, & Macnaghten, 2013). With this shift comes increasing interest (particularly from government) in public engagement with emerging technologies, and importantly; how best to engage the public.

Public engagement is often motivated by normative, substantive, or instrumental concerns. Normative democratic ideals suggest the public should have a say in the emerging technologies that will affect them (Fiorino, 1990; Stilgoe et al., 2014; Stirling, 2008). Public engagement can also achieve substantive outcomes by informing and improving decision-making (Chilvers, 2009; Rogers-Hayden & Pidgeon, 2007). Finally, public engagement is often used toward instrumental ends, such as legitimising decision making and enhancing institutional trust (Chilvers, 2009; Rogers-Hayden & Pidgeon, 2007).

As with many radical innovations, there is a risk that public opposition could – for better or worse – stymie the adoption of emerging climate technologies, rendering decades of research and development wasted (see 7.0 Appendices for more information). Thus, it is critically important that scientists and policymakers engage civil society early in the research and development process to identify mutually acceptable technological pathways. However, this early or *upstream* public engagement raises a unique challenge known as Collingridge's (1980) *Dilemma of Control*: There are substantial *uncertainties* and *unknowns* with emerging technologies that will not reveal their extent without further research, development, and implementation. However by the time these uncertainties are resolved, it may be too late to halt or change the trajectory (Rogers-Hayden & Pidgeon, 2007), due to the considerable research, development, funding, and interests already vested in the technologies. Consequently, by the time most of the public are exposed to these technologies, it is often too late for their emergent concerns to significantly affect their trajectories, leading to controversy and public backlash (Wilsdon & Willis, 2004). The European Union's moratorium on genetically modified organisms (GMO) is a prime example where large-scale protests eventually quashed GMO implementation in the European Union.

The solution is to shift public engagement *upstream*, where public concerns can still influence the early development of technologies before trajectories become entrenched (Wilsdon & Willis, 2004). However, conducting upstream public engagement is not without significant challenges. Public awareness is typically low for emerging technologies (Cummings, Lin, & Trump, 2017) and therefore, researchers must provide enough context for lay citizens to evaluate unfamiliar concepts (Corner & Pidgeon, 2010; Corner, Pidgeon, & Parkhill, 2012). Consequently, the researchers' choices of what information to present and what questions to ask requires careful attention to avoid biasing citizens' evaluations.

In response to these challenges, researchers have become increasingly interested in deliberative methods of upstream public engagement such as focus groups, citizens juries, and facilitated workshops (Bellamy, Chilvers, Vaughan, & Lenton, 2012; Bellamy & Lezaun, 2017; Corner & Pidgeon, 2010). Unlike traditional techniques such as qualitative interviews or quantitative surveys, deliberative approaches generally involve some form of in-depth facilitated discussion amongst small groups of self-selected citizens. One key reason for researchers' interest in deliberative methods is that they empower participants to frame the discussion themselves (Bellamy et al., 2012) and therefore mitigate the risk of framing effects introduced via the research design. Another reason for researchers' interest in deliberative methods is that, compared to traditional survey questionnaires, they purportedly elicit more considered responses from participants (Macnaghten & Szerszynski, 2013). However, it remains unclear whether this greater consideration substantively improves research outcomes.

There is no doubt that deliberative approaches are effective tools for "opening-up" technology appraisals by challenging researchers underlying assumptions (Bellamy & Lezaun, 2017) and they certainly provide valuable insights into the nuances of citizens' perceptions. However, as with any methodology, deliberative approaches have several limitations. First, deliberative exercises are resource intensive and difficult to conduct on a large scale. For example, deliberative workshops involving a handful of participants may require several multi-hour facilitated sessions over the course of several days. Consequently, scaling deliberative methodologies nationally or internationally is limited by substantial resource and coordination requirements, raising issues of inclusivity and representativeness. Recruiting participants is also challenging due to the substantial time commitment required, and the potential for self-selection biases. Finally, deliberative processes require a high level of participant engagement in the topic that citizens are unlikely to pursue of their own volition (Merk et al., 2019), raising questions about the external validity of the research findings. Put simply, it is unclear whether citizens' deliberative evaluations of emerging technologies are reflective of the wider public's reactions.

Traditional survey methodologies address many of these issues. Self-administered surveys are easily scalable, allowing researchers to elicit public opinion across countries with representative samples at relatively low cost. However, traditional survey-based public engagement also raises several methodological concerns including acquiescence bias, non-attitudes (Asher, 2017), framing effects (Bellamy et al., 2012), and a profound ambivalence toward emerging science (Corner & Pidgeon, 2010).

Given the limitations of current public engagement methodologies, there is a clear need to introduce new and innovative methodologies into the public engagement discipline. One research domain with substantial experience in evaluating emerging concepts is Marketing (Wright et al., 2014). The marketing discipline has strong connections to well-established psychological concepts, such as *associative network theories of memory* (Anderson, 1983; Anderson & Bower, 1973; Romaniuk, 2013) and *dual processing theories* of human reasoning (Evans, 2011; Konopka, Wright, Avis, & Feetham, 2019) that explain public perceptions and behaviour. Within the marketing discipline, Market Researchers have also developed several well-established techniques for engaging the public and evaluating unfamiliar concepts (Wright et al., 2014).

Despite these clear parallels between public engagement and marketing disciplines, the potential for interdisciplinary advancements remains largely unexplored. Thus, the purpose of this thesis is to advance public engagement with emerging technologies using marketing theories and market research techniques. The thesis involves three studies that draw on recently developed market research techniques to explore and quantify public perceptions of emerging climate technologies, namely *climate engineering* and *alternative shipping fuels*[1]. The research in this thesis makes several theoretical and methodological contributions that not only advance public engagement, but also further validate their use in the marketing discipline. These theoretical and methodological advancements are outlined in the following subsections.

1.2. Market research and public engagement

Market researchers are lead users in techniques to engage the public (i.e., customers), understand their perceptions of products and services, and develop offerings to suit (Wright et al., 2014). Whether evaluating complex emerging technologies or the latest iPhone, the basic premise remains the same: Developing offerings that satisfy societies' wants and needs. Accordingly, several market research techniques are easily adapted to understand public perceptions of emerging technologies and provide insights that shape research, development, and policy.

Public engagement already shares several methodologies with market research, including qualitative focus groups, quantitative survey questionnaires, and experimental designs (Cummings et al., 2017). Some specialised market research techniques have also gained traction within public engagement, including conjoint analysis (e.g., Wallquist, Seigo, Visschers, & Siegrist, 2012), and more recently, techniques for modelling cognitive associations (Wright et al., 2014). This latter technique, developed by market researchers to model consumers cognitive associations with brands (Romaniuk, 2013), is the core methodological focus of this thesis (section 1.2.1).

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[1] Climate engineering refers to a range of technologies for removing carbon-dioxide from the atmosphere, or artificially cooling the planet. Alternative Shipping Fuels refer to low-carbon alternative fuel sources for marine propulsion (see section 7.0 for more detail).

1.2.1. Modelling cognitive associations

The cognitive association methodology used in this thesis is adapted from a brand metric technique for modelling *mental market share* (Romaniuk, 2013). The technique is grounded in Associative Network Theories of Memory (ANTM) that explain how individuals encode, retain, and retrieve information from memory (Anderson & Bower, 1973). Information is coded in human memory as *nodes* connected by *associative links* to form an *associative network*. Information is retrieved from the associative network through a process of *spreading activation*. Stimuli causes activation to spread between nodes via the associative network, retrieving the information into working memory. Once the activation source drops from attention, activation begins to decay, and the information falls back out of working memory (Anderson, 1983; Anderson & Bower, 1973).

ANTM has obvious applications in marketing: In choice situations, consumers draw on information from their associative network to select between brands. Thus, marketers aim to build and refresh their brands' associative network in consumers' minds to increase the likelihood of retrieving the brand from memory during a choice situation (i.e., top of mind), and therefore increase the likelihood of purchase. To assist marketers in their efforts and provide feedback on their effectiveness, brand researchers developed techniques to model the size and structure of a brands *associative network*, relative to competing brands (Romaniuk, 2003, 2013).

Wright et al. (2014), later adapted this method to measure citizens cognitive associations (i.e., perceptions) with emerging climate technologies. Building on their work the studies in this thesis introduce further methodological innovations: The first publication demonstrates the ability to benchmark and track perceptions as they evolve over time (using datasets from 2012 and 2018), providing crucial feedback to industry and policymakers to guide decision-making and development trajectories. The second publication offers evidence that measuring citizens' initial reactions yield the same responses as participants that take time to consider their responses, thereby validating the use of survey methodologies for rapid, cross-country public engagement activities as an alternative to more in-depth deliberative techniques. The final publication demonstrates the extendibility of the method to a related domain (i.e., alternative shipping fuels). This publication also supplements the quantitative findings with data from the qualitative interviews, providing richer insights into the drivers behind participants' perceptions. Though mixed-method approaches are not themselves a novel innovation, it appears this publication is the first to do so in academic literature using the quantitative cognitive association approach.

1.2.2. Dual processing

In addition to ANTM and cognitive association methodologies, this thesis also draws on *dual process* theories of human reasoning. Dual process theories suggest cognition occurs through two distinct types of information processing (Evans, 2011). The bulk of everyday cognitive tasks rely on intuitive Type 1 processing. This fast and frugal processing relies on heuristics (i.e., mental shortcuts) to conserve cognitive resources, but is prone to systematic errors and biases (Kahneman, 2011; Kahneman, Slovic, & Tversky, 1982). Deliberative Type 2 processing can override initial Type 1 reactions using slower, reflective information processing. While Type 2 processing can overcome errors and biases associated with Type 1 intuitions, it requires significantly more cognitive resources and effort (Evans, 2003; Evans & Stanovich, 2013; Kahneman, 2011).

Dual process theories are well established in cognitive psychology and have been applied to several areas of marketing, including persuasion (Petty & Cacioppo, 1986), advertising (Nairn & Fine, 2008), and brand choice (Konopka, 2018); and have clear parallels and applications for public engagement surveys. For example, some public engagement researchers have expressed concern that survey methodologies elicit superficial (Type 1) reactions, rather than thoroughly considered (Type 2) responses (Macnaghten & Szerszynski, 2013). Since Type 1 and Type 2 reasoning can cause individuals to arrive at different conclusions (Evans & Stanovich, 2013) there is a risk that different methods of public engagement may arrive at different conclusions. Consequently, it is also unclear whether deliberative (Type 2) methods elicit perceptions that reflect the wider public's intuitive (Type

1) judgements. The experimental findings in Publication Two challenge these concerns and show that reflective Type 2 responses are no different to intuitive Type 1 reactions. This is an important finding for public engagement researchers and validates the use of quantitative surveys in public engagement. Additionally, this finding demonstrates the usefulness of survey methodologies, as an alternative to more in-depth deliberative methodologies, for quickly collecting representative, cross-country data on a large scale; a critical task required to establish a global understanding of public perceptions toward emerging technologies. This study, and the two introduced in section 1.2.1 are discussed further below (Section 1.3).

1.3. Thesis aims, contributions, and structure

The overarching aim of the three studies in this thesis is to apply marketing theories to address some of the challenges of public engagement (described above). In particular, the thesis aims to further validate the use of cognitive association methodologies via replication in additional countries and over time (Publication 1); examine the extent that deliberation affects participants responses within a dual processing framework (Publication 2); and cross-validate the quantitative findings against qualitative insights (Publication 3).

In line with these aims, this thesis adopts a realist ontology that seeks to undertake empirical research that is, in principle, reproducible and intersubjectively verifiable. This is not to deny the importance of relativist, interpretivist, or constructivist approaches, but simply to note the position of this research within a broader epistemological framework. The research does seek to use mixed-methods by combining qualitative insights with survey methods. However, these methods follow a defined procedure to elicit measurable responses, rather than attempt to draw conclusions about the internal mental states of the respondents or the construction of the social environment within which these responses are given. Accordingly, all three studies in this thesis follow similar methodologies and begin with an exploratory qualitative phase. The outputs of the qualitative research are used to design the primary measures in subsequent large-scale quantitative surveys. The following sections outline the research approach for each of the publications, the overarching thesis contributions, and conclude by outlining the remaining thesis structure.

1.3.1. Publication one

The first publication "*The public remain uninformed and wary of climate engineering*" (Chapter 2.0) replicates the original study by Wright et al. (2014) comparing baseline perceptions in Australia and New Zealand from 2012, against updated measures in 2018. Two additional 2018 samples from the United States and United Kingdom provide further comparative data. The study addresses the following research questions:

RQ1.1 To what extent to public perceptions of climate engineering differ between technologies?

RQ1.2 To what extent do public perceptions of climate engineering differ between countries?

RQ1.3 To what extent have public perceptions of climate engineering evolved between 2012 and 2018?

The remarkable consistency between countries and over time further validates the robustness of the method for measuring public perceptions. However, the main advancement is demonstrating the ability to not only compare perceptions between countries, but benchmark and track perceptions as they evolve. The validation of the cognitive association method for perception tracking research, and the demonstration of robustness of the measures to changes in survey context, allow industry and policymakers to now easily and effectively monitor and react to public concerns as awareness and perceptions of these technologies evolve.

1.3.2. Publication two

The second publication *"Public engagement with emerging technologies: Does reflective thinking affect survey responses?"* (Chapter 3.0) reports an additional UK based experiment, conducted in parallel with the first publication. Some researchers have voiced concern about whether respondents have enough time and information to provide thoroughly "considered" opinions during brief survey questionnaires (Macnaghten & Szerszynski, 2013; Merk et al., 2019). Therefore, the second publication draws on dual processing theories of human reasoning (Evans, 2003) to test whether encouraging participants to engage in slower, reflective thinking (or fast, intuitive thinking) affects their perceptions of emerging climate technologies. The study addresses the following research questions:

RQ2.1 To what extent does encouraging intuitive or reflective thinking affect public perceptions of climate engineering?

RQ2.2 To what extent do public perceptions of climate engineering differ between participants who choose to consider their responses for longer than those that respond quickly?

Despite a successful manipulation check, encouraging reflective thinking had no impact on participants' perceptions. More importantly, the findings provided evidence that the public typically rely on automatic snap judgements – not thorough consideration – when forming opinions on emerging technologies. This is an important finding as it suggests, contrary to researchers' concerns, that participants' rapid survey responses are indeed reflective of broader public opinion. Thereby providing additional validation to quantitative methods of public engagement.

1.3.3. Publication three

The third and final publication *"Public response to decarbonisation through alternative shipping fuels"* (Chapter 4.0) shifts focus from climate engineering to emerging fuels for decarbonising the shipping sector. At the time of writing, no peer reviewed research has investigated public perceptions of alternative shipping fuels. With growing calls to decarbonise shipping (*Call to Action for Shipping Decarbonization*, 2021), this research breaks fresh ground as the first to assess UK perceptions of six alternative shipping fuels. Additionally, the publication outlines further methodological advances, as the first to combine Romaniuk's (2013) cognitive association technique with qualitative analysis in a mixed-method approach. The study addresses the following research question:

RQ3.1 What are the UK public's perceptions of alternative shipping fuels?

Again, the quantitative analysis produced excellent comparative data on public perceptions with potential for significant impact on the development trajectory of alternative marine fuels. However, supplementing these findings with the qualitative data proved a worthwhile addition, offering rich insights into the drivers behind participants' perceptions and concerns. These insights are particularly critical for exploratory studies, as in Publication Three, where public perceptions were previously unknown.

1.3.4. Contributions overview

Practical implications for emerging climate technologies

The results of cognitive association measurement reported in this thesis identify significant differences in public reaction to emerging climate technologies. These include confirmation of the striking difference in the favourability of Carbon Dioxide Removal (CDR) over Solar Radiation Management (SRM), a surprising preference for nuclear propulsion over the incumbent heavy fuel oil, a preference for implementing hydrogen and biofuel for marine propulsion, a "yes in my back yard" (YIMBY) effect supporting local implementation of alternative shipping fuels, and conditional support for small-scale research that varies between emerging climate technologies. Full details can be found in the individual papers with a summary in section 5.0.

Theoretical and methodological contributions

This thesis makes several methodological and theoretical contributions (Section 5.2.1): First, it provides additional validation for the application of *associative network theories of memory* (ANTM; Anderson, 1983; Anderson & Bower, 1973) and cognitive association methodologies (Romaniuk, 2013; Wright et al., 2014) for conducting public engagement with emerging technologies, thereby eliciting valuable insights into public and consumer perceptions. Second, the findings contribute to the marketing discipline by demonstrating that ANTM, and cognitive association methodologies are robust and hold across different disciplines. Third, it introduces *dual processing theories* of human reasoning into the public engagement discipline, providing insights into how public opinions about emerging technologies are formed. Fourth, it demonstrates the validity of survey methodologies as a rapid measure of citizen and consumer judgements. Fifth, it establishes a mixed-method approach to modelling cognitive associations and demonstrates the value of supplementing quantitative public engagement studies with qualitative insights.

Implications for public engagement research

The above contributions have implications for public engagement research (Section 5.2.2): The first and third studies demonstrate the usefulness of cognitive association techniques for rapidly conducting large-scale, cross-country public engagement research. Contrary to social scientists' concern, the second study also validated the use of survey mechanisms for eliciting rapid, but stable perceptions of emerging technologies. Finally, the third study also introduced and demonstrated the value of a mixed-method approach to modelling cognitive associations. Moving forward, by drawing from the marketing discipline these studies provide a robust framework and benchmark for public engagement researchers to track perceptions of the tested technologies and other innovations as they evolve over time.

Implications for scientists, policymakers, and industry.

In addition to quantifying public perceptions of emerging climate technologies, the research also demonstrated the need for scientists, policymakers, and industry to consider how emerging technologies align with public opinion and concerns (Section 5.2.3). For scientists, measurement of public perceptions can inform their research activities and help ensure they follow publicly acceptable research and development pathways. For policymakers, this information can provide insight into areas of public concern and ensure that appropriate policies are developed prior to large-scale implementation. For industry, it can aid decision-making and ensure substantial investment of time and resources are not wasted on publicly unacceptable technologies. Ultimately, ongoing public engagement research can inform decision-making, guide technological trajectories, and identify publicly acceptable decarbonisation pathways in the fight against climate change.

1.3.5. Thesis structure

The rest of the thesis is structured as follows: Chapter 2.0, 3.0, and 4.0 contain the three articles that form this thesis by publication. Chapter 5.0 concludes the thesis and summarises the key findings, contributions, implications, and future research.

ARTICLE 1:
THE PUBLIC REMAIN UNINFORMED AND WARY OF CLIMATE ENGINEERING

Preface:

This chapter contains work already published by the authors in the peer reviewed journal *Climatic Change* (Impact Factor: 4.743). The final authenticated version is available at the DOI below.

Carlisle, D. P., Feetham, P. M., Wright, M. J., & Teagle, D. A. H. (2020). The public remain uninformed and wary of climate engineering. *Climatic Change, 160*(2), 303-322. https://doi.org/10.1007/s10584-020-02706-5

The full article and supplementary information are reproduced in the following chapter. While the article structure and content are preserved, some minor changes are made to ensure consistency across this thesis. The reference list is also aggregated at the end of the thesis.

This project has been evaluated by peer review and judged to be low risk (4000020070)

Summary:

Aim: Compare public perceptions of six climate engineering technologies across four countries, and over time (2012 and 2018).

Main Research Questions:

RQ1.1 To what extent to public perceptions of climate engineering differ between technologies?

RQ1.2 To what extent do public perceptions of climate engineering differ between countries?

RQ1.3 To what extent have public perceptions of climate engineering evolved between 2012 and 2018?

Method: Qualitative depth interviews (NZ convenience sample; $n = 30$) followed by large scale quantitative surveys (NZ, Australia, UK, US; $n = 3{,}011$). Compared against comparative 2012 data collected by Wright et al. (2014).

Findings: Perceptions of climate engineering were remarkably consistent between countries and surprisingly stable over time.

Contributions: The findings provide a timely and critical update on public perceptions of climate engineering to inform ongoing research, development, and policymaking. The consistency between samples validates the robustness of the method for eliciting public perceptions. The comparisons over time demonstrate the effectiveness of the method for establishing baseline measures to track public perceptions as they evolve in parallel with the development of emerging technologies.

MASSEY UNIVERSITY
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STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Daniel Carlisle
Name/title of Primary Supervisor:	Prof. Malcolm Wright
Name of Research Output and full reference:	
Carlisle, D. P., Feetham, P. M., Wright, M. J., & Teagle, D. A. H. (2020). The public remain uninformed and wary of climate engineering. Climatic Change, 160(2), 303-322. https://doi.org/10.1007/s10584-020-02706-5	
In which Chapter is the Manuscript /Published work:	2
Please indicate:	
• The percentage of the manuscript/Published Work that was contributed by the candidate:	60%
and	
• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
Daniel led the research design, fieldwork, data analysis and drafting the article.	
For manuscripts intended for publication please indicate target journal:	
Candidate's Signature:	[signature]
Date:	02-Jun-2022
Primary Supervisor's Signature:	Wright, Malcolm Digitally signed by Wright, Malcolm Date: 2022.06.01 14:37:07 +12'00'
Date:	1-Jun-2022

(This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis)

2.0 The public remain uninformed and wary of climate engineering

Abstract: International CO_2 emissions reduction commitments are insufficient to avert damaging global warming and imperil a sustainable future. Climate engineering approaches are increasingly proposed as near-term intervention strategies, but deployment of these controversial techniques will require careful engagement with and the support of the public. New quantitative measurements of public perceptions for six climate engineering approaches show that the public of the United Kingdom (UK), United States (US), Australia (AU), and New Zealand (NZ) continue to have little knowledge of climate engineering. All approaches are regarded unfavourably, albeit less so for Carbon Dioxide Removal (CDR) than Solar Radiation Management (SRM). Knowledge and perceptions are remarkably similar between countries although UK and US respondents are more favourable towards SRM, and UK respondents are more favourable towards CDR. Stratospheric Aerosol Injection is the most negatively perceived approach. Support for small-scale trials is also higher for CDR approaches than SRM. Statistical analyses yield mixed relationships between perceptions of climate engineering and age, political affiliation, and pro-ecological views. Thus far, attempts to engage the public with climate engineering have seen little change over time and consequently, there is growing urgency to facilitate careful citizen deliberation using objective and instructive information about climate engineering.

2.1. Introduction

Following COP 21 in Paris, 194 nations agreed to limit future global warming to less than 2°C above pre-industrial levels, although <1.5°C is a preferred target for many nations. These 194 nations face significant challenges and decisions on their pathways to reducing greenhouse gas emissions. The agreed actions to date are insufficient to achieve the targets (Bawden, 2016; Lawrence et al., 2018; Schleussner et al., 2016) with the current Paris pledges providing less than half the emissions reductions required (UNEP, 2018). Many national Net-Zero ambitions rely on substantial negative emissions to balance CO_2 inputs from difficult to decarbonise sectors (e.g., cement, land-use, shipping, air travel), but remain imprecise about how this CO_2-drawdown will be achieved. The unlikelihood of reaching the Paris goals through mitigation alone has prompted new calls for globally governed research into potential large-scale climate engineering approaches (Bellamy & Healey, 2018; Biermann & Möller, 2019; Ki-moon, 2019) including Carbon Dioxide Removal (CDR) approaches that sequester atmospheric carbon dioxide and Solar Radiation Management (SRM) methods that alter the radiative forcing of Earth's atmosphere (Horton, 2015; Lawrence et al., 2018).

Researchers worldwide report on-going technological advances and continue to develop knowledge of climate engineering feasibility and impacts (Irvine et al., 2019; Lawrence et al., 2018; MacMartin, Ricke, & Keith, 2018; Royal Society & Royal Academy of Engineering, 2018; Salter, Stevenson, & Tsiamis, 2014; J. P. Smith, Dykema, & Keith, 2018). Initiatives such as the Geoengineering Model Inter-comparison Project (GeoMIP) allow scientists to conduct multiple climate modelling simulations to estimate the likely global impacts of particular climate interventions (Kravitz et al., 2019; Kravitz et al., 2018). Interest is also building in the Harvard based Stratospheric Controlled Perturbation Experiment (SCoPEx) project that would release aerosols from a balloon to study aerosol physics and chemistry related to some SRM approaches. Following the 2012 withdrawal of the similar UK based 'SPICE' project, SCoPEx would be the first explicit field test of SRM technologies (Tollefson, 2018). Currently, uncertainty remains around the global impacts of climate engineering as most research is restricted to computer modelling or controlled laboratory settings (Lawrence et al., 2018). Scientists are also careful to point out that climate engineering is not a panacea for failure to achieve emissions reductions, and must be deployed in concert with, rather than a distraction from accelerated improvements in energy efficiency and greenhouse gas emissions reduction efforts (Royal Society & Royal Academy of Engineering, 2018).

The warnings for more action on Paris Agreement targets highlight the urgency for researchers and policy makers to engage the public in the development of potential solutions including climate engineering approaches (Burns et al., 2016; Rayner et al., 2013) before societies are confronted with the necessity of deploying such techniques at scale. Despite increasing research on public perceptions of climate engineering (Cummings et al., 2017) there are still substantial gaps in the literature. Few studies investigate public perceptions in the global south (Burns et al., 2016) or over time (Braun, Merk, Poenitzsch, Rehdanz, & Schmidt, 2018; Braun, Rehdanz, & Schmidt, 2018).

The present quantitative work, therefore, examines public perceptions of climate engineering in surveys conducted across four countries and innovatively, over time. It is the first study to systematically measure public perceptions from surveys conducted in the United Kingdom (UK), United States (US), Australia (AU) and New Zealand (NZ) in December 2018, against previous measurements derived from surveys conducted in AU and NZ in December 2012 (Wright et al., 2014). The method draws on well-established psychological theory and marketing techniques to elicit and measure cognitive associations with new product concepts or brands (Anderson, 1983; Anderson & Bower, 1973; Romaniuk, 2013; Wright et al., 2014). The present work substantively expanded the original study with fresh fieldwork that drew on new knowledge and technological advancements within the field of climate engineering, as well as further understanding of framing effects raised in recent literature. We also examine the associations with demographics, ecological views, and political party affiliation on public perceptions of climate engineering and whether the public would support small scale trials for each of the six approaches. The resulting analysis provides a robust system that quantifies public perceptions of climate engineering and provides a benchmark for future comparisons of public opinions by sampling across multiple countries and over time. Tracking public opinion, whether changed or stagnant, over time provides imperative information for policy makers and those organisations responsible for collaborating and communicating with the public on potential climate solutions.

2.1.1. Public engagement with emerging technologies

Public engagement is increasingly sought as a key element of the governance of emerging science and technology. Over the years, three key arguments have emerged to promote public participation (Chilvers, 2009; Fiorino, 1990; Stirling, 2008; Wilsdon & Willis, 2004; Winickoff, Flegal, & Asrat, 2015). The normative rationale suggests public participation is necessary in democracy and that the public have a right to be involved in policy that will affect them. The substantive rationale claims that public participation can improve decision-making and outcomes by incorporating diverse knowledge and viewpoints. Finally, the instrumental rationale suggests participation can achieve specific outcomes including increasing trust in science, enhancing legitimacy of institutions, and avoiding conflict. The latter substantive and instrumental outcomes are rarely evidenced in practice (Chilvers, 2009), leading to the question of what value public participation might provide beyond the tokenistic attempts at democracy. Nonetheless, the growing impetus for public engagement with science is apparent across a range of emerging technologies (Stirling, 2008), such as nanotechnologies (Rogers-Hayden & Pidgeon, 2007), and climate engineering (Bellamy & Lezaun, 2017; Corner et al., 2012).

Social scientists also differentiate between three types of public engagement mechanisms (Rowe & Frewer, 2005). *Public Communication* mechanisms involve a passive process where the public receive information, but do not play an active role in informing decision making; *public consultation* mechanisms, including the current study, are used to elicit opinions from the public; and *public participation* mechanisms involve dialogue between stakeholders and the public to share knowledge and negotiate understanding. Each of these types of public engagement have inherent flaws. One main criticism relates to public communication mechanisms and the 'deficit' model of science communication. The deficit model assumed that educating the public through communication mechanisms would improve citizens' perceptions of science (Corner & Pidgeon, 2010). Contemporary public consultation and public participation mechanisms reject the deficit model and imply citizens can make informed judgements in the absence of technical knowledge under the right conditions (Wilsdon & Willis, 2004).

Given the global significance of climate engineering, large-scale public consultation methods, are needed to provide systematic measurement of public opinion across global populations. Quantitative surveys address these needs but are typically restricted by narrow standardised measures of 'acceptance' or 'support'. These attitudinal measures are criticised for disregarding more nuanced positions and overlooking participants underlying reasoning. Accordingly, there is concern among social scientists that quantitative survey research may not reflect actual public opinion and could exclude legitimate policy alternatives from future consideration (Bellamy et al., 2012). One method of addressing these concerns are small-scale participatory mechanisms that encourage citizens to engage in nuanced discussions and challenge the underlying assumptions that shape the appraisal process. For example, Bellamy, Chilvers, and Vaughan (2016) report a deliberative appraisal method where participants developed their own appraisal criteria that better reflect the small groups' opinions on climate engineering proposals. To address these concerns, the current study draws on participative elements in an initial qualitative phase to identify a list of citizen-generated appraisal criteria that are later applied in the quantitative phase of public consultation.

2.1.2. Framing the climate engineering debate

Eliciting public opinion on emerging technologies is particularly challenging as citizens are often unfamiliar with the technologies in question. One issue is that survey instruments may elicit 'non-attitudes' where participants respond to questionnaire items despite holding no genuine prior opinion on the matter (Asher, 2017). These non-attitude responses are often sensitive to minor changes in questionnaire wording and may distort measures of public opinion. Researchers have therefore raised concerns about the way climate engineering is framed during public engagement.

One framing concern is that CDR and SRM approaches should not be lumped together under the broad umbrella term ‘climate engineering’ as CDR approaches are substantially different from SRM (Heyward & Rayner, 2013; Lomax, Workman, Lenton, & Shah, 2015; Minx et al., 2018). CDR approaches share greater similarities with mitigation strategies that reduce atmospheric carbon concentrations, whereas SRM approaches do not (Minx et al., 2018). Another framing concern is that the higher risk profile of SRM approaches will negatively affect perceptions of CDR approaches, forestalling their serious consideration (Colvin et al., 2019; Horton, 2015). Given the substantial differences within CDR and SRM categories, Colvin et al. (2019) argue individual technologies should be considered independently to facilitate nuanced discussion and avoid sweeping generalisations. Other framing issues are the need to evaluate climate engineering approaches within the broader context of alternative strategies such as mitigation and adaptation (Bellamy et al., 2012; Bellamy & Lezaun, 2017), to ensure that linguistic frames avoid use of natural analogies, such as likening air capture to ‘artificial trees’ (Corner & Pidgeon, 2015), and to recognise that terms such as ‘insufficient mitigation’ or ‘climate emergency’ narrow and pre-empt the direction of discussions (Bellamy, Chilvers, Vaughan, & Lenton, 2013; Bellamy & Lezaun, 2017; Corner, Parkhill, & Pidgeon, 2011).

Since there is concern among social scientists that framing may have undue effects on perspectives of climate engineering, we take care to minimise such effects. We avoid the term climate engineering and instead refer to potential solutions to rising global temperatures. We avoid the use of natural analogies (Corner & Pidgeon, 2015) and statements about a ‘climate emergency’ or ‘insufficient mitigation’(Bellamy et al., 2013; Corner et al., 2011). We define responses as distinct policy options alongside adaptation and mitigation, present the approaches individually, and apply new scientific knowledge to update the descriptions and images used.

2.2. Methods

The research method is validated in two ways. First, its theoretical foundations are well established in cognitive psychology. Second, the brand imaging techniques developed from these theories by branding experts are widely applied commercially. The method's founding theories of Associative Network Theory of Memory (ANTM) and the Adaptive Control of Thought model (Anderson, 1983; Anderson & Bower, 1973) describe how a concept is encoded, retrieved and stored in memory. When humans are faced with an external stimulus such as an image or concept description, information stored in memory actively cascades through a network of associated nodes to help with interpretation and problem solving (Wright et al., 2014). Brand experts developed these theories to systematically and quantitatively elicit cognitive associations with concepts or brands that are mapped in images (Romaniuk, 2013; Wright et al., 2014). The 2012 study demonstrated that this system adapts to other domains such as emerging science by measuring the attributes associated with climate engineering proposals and is replicated in this study.

The surveys undertaken in 2012 commenced with qualitative research on climate engineering associations (n = 30) followed by quantitative data collection (n = 2028) on the public perceptions of three CDR approaches *Biochar, Air Capture, Enhanced Weathering,* and three SRM approaches *Cloud Brightening, Stratospheric Aerosols* and *Mirrors in Space* (Wright et al., 2014). The 2018 surveys undertook new qualitative research (n = 15) followed by new quantitative data collection (n = 2989) for Bioenergy with Carbon Capture and Storage (*BECCS*), Direct Air Capture and Carbon Storage (*DACCS*), Enhanced Weathering (*EW*), Marine Cloud Brightening (*MCB*), Stratospheric Aerosol Injection (*SAI*) and Mirrors in Space (*MIS).* Since the choice of climate engineering approaches can affect research outcomes (Bellamy et al., 2012), we acknowledge the current study excludes other possible climate engineering approaches (e.g. biochar, cirrus cloud thinning, and afforestation) and outline the rationale behind our choices. Public perceptions of *BECCS* remain understudied (Bellamy, Lezaun, & Palmer, 2019) despite playing a major role in several modelling scenarios to meet 1.5°C or 2°C targets, in the IPCC (2014) Fifth Assessment Report. Therefore, *BECCS* replaces *Biochar* for evaluation to maintain a balance of three CDR and three SRM approaches. Replacing MIS was also considered due to issues of feasibility. However, public and policy interest in MIS has continued to be expressed, for example with American democratic candidate Andrew Yang campaigning on providing $800 million USD in funding for SRM research, including MIS. Thus, MIS is retained in the current study. Table 3 briefly summarises the CDR and SRM approaches from the 2012 and 2018 surveys.

Table 3: Approaches for Carbon Dioxide Removal and Solar Radiation Management

Carbon Dioxide Removal		
Biochar	-	Biomass is converted into a charcoal-like product to lock-in carbon.
Bioenergy with carbon capture and storage	BECCS	Biomass is combusted to produce renewable energy and carbon dioxide emissions are captured and stored in geological reservoirs.
Direct Air Capture and Carbon Storage	DACCS	Carbon dioxide is filtered from the atmosphere using engineered structures and stored in geological reservoirs.
Enhanced Weathering	EW	Materials (e.g., silicate minerals) are finely ground to accelerate chemical reactions that remove carbon dioxide from the atmosphere.
Solar Radiation Management		
Marine Cloud Brightening	MCB	Tiny seawater droplets are sprayed into low altitude marine clouds to increase their reflectivity.
Mirrors in Space	MIS	Space-based materials or structures reflect a portion of incoming sunlight.
Stratospheric Aerosol Injection	SAI	Sulphate particles are spread in the stratosphere to reflect incoming sunlight.

For further reading on CDR and SRM see Lawrence et al. (2018), US NAS (2015a), US NAS (2015b), Royal Society and Royal Academy of Engineering (2018).

To reflect recent advances in scientific knowledge we update the descriptions of each climate engineering approach used in the 2012 materials and draw on recent imagery used by the Royal Society and Royal Academy of Engineering (2018) and Lawrence et al. (2018). The concept boards

(Figure 4) use consistent formatting and content across techniques. Descriptions begin with three sentences describing the concept, method of application and advantages, including the cooling effect and other benefits. Next, two or three sentences outline the costs, possible unintended outcomes and any caveats associated with implementation. The final two or three sentences outline how the method would be implemented over time, the scale of implementation required, and indicate whether the method would require international agreements. Final descriptions are between 93-100 words and avoid use of adjectives from the attribute list. Some similar or identical phrases are used in multiple approaches where appropriate. Imagery is designed following similar matching criteria for scale, content, and colour. As in the original study, we do not attempt to evaluate visual processing of imagery. The concept boards and questionnaires were peer-reviewed within the authorship team with additional feedback solicited from two independent international experts and from citizens within the sampling frame. Minor word adjustments were applied after this feedback and the concepts boards were further validated through successful application in the qualitative interviews (n = 15).

2.2.1. Qualitative phase (2018)

The aim of the qualitative phase is to explore the ways that citizens think about the topic to identify any new constructs associated with climate engineering approaches compared to the 2012 research (Wright et al., 2014). The output of this phase is a set of common attributes that are used in the quantitative phase as criteria for evaluating climate engineering approaches. Using attributes (criteria) developed by citizens incorporates diverse and inclusive public perspectives to 'open up' the quantitative appraisal process (Bellamy et al., 2016). Whereas criteria generated by experts or researchers may not accurately reflect public perspectives and could bias appraisal outputs.

The qualitative phase includes fifteen in-depth interviews using the Kelly's Repertory Grid elicitation technique and follows the method previously applied in the qualitative phase of the 2012 study (Rogers & Ryals, 2007; Wright et al., 2014). The convenience sample is purposively selected from the authors' networks to maximise demographic diversity and consists of 53% female and 47% male

New Zealanders, aged between 21 and 63 years, and with varied occupations (Table 7). The Kelly's Repertory Grid technique invites participants to identify two concepts out of a set of three, and to explain how the pair are alike yet different from the third. The method in this case is used to identify a list of attributes associated with each climate engineering approach. Prior to the exercise, participants read all six concept boards. Participants were then sequentially presented with six sets of three concept boards to evaluate similarities and differences. Sets were predetermined to ensure each concept was evaluated three times. The presentation order of the six sets and the order of three concept boards within each set was randomised by the interviewer. Responses were audio-recorded and analysed by themes to identify, group, and total attributes commonly elicited from participants. The attributes emerging from the qualitative phase in 2018 were congruent with those uncovered in the 2012 study. We therefore proceeded to the quantitative phase using the same 12 attributes as the earlier study (Wright et al., 2014).

2.2.2. Quantitative phase (2018)

Sampling

The quantitative phase consists of large-scale surveys in the United Kingdom (number of participants, *n* = 751), United States (*n* = 746), Australia (*n* = 763), and New Zealand (*n* = 729), using a commercial online panel provider; Dynata (formerly ResearchNow, https://www.dynata.com). Survey invitations are topic-blind to mitigate response bias. Invitations are issued to panel members continuously until sample and demographic quotas are met. Recruitment bias is unlikely given the substantial size of the panels (*n*=1,200,000 in the United Kingdom, *n*=11,570,000 in United States, *n*= 780,000 in Australia, and *n*=260,000 in New Zealand). Coverage bias is also minimised with high levels of internet access in all four countries[2]. The surveys were conducted in early December (week commencing 30 November) 2018, the same time of year as the 2012 study (Wright et al., 2014).

Participants

Tables 8-11 report the demographic breakdown of the quantitative samples along with comparative census data or similar independent population estimates for gender, age, and political support. The sample characteristics for each country show a satisfactory spread of demographics with overall only small deviations from population estimates. Therefore, sample composition is acceptable for the purposes of this research.

Data collection

The survey questionnaire is the same for all countries except for minor differences in demographic items. The questionnaire was pretested among several survey design experts and non-experts who experienced no major difficulties in interpreting questions, understanding the concepts, or the survey flow. Minor improvements were made to the survey design after this feedback. Prior to the survey's full launch, responses from 70 initial participants were checked to ensure the questions were not misunderstood. No further changes were made, and the full launch proceeded until quotas were achieved.

The questionnaire prepares participants to give meaningful responses by briefly introducing the topic and asking general questions about global warming (see Figure 3 for questionnaire wording). Respondents then move to the concept evaluation block where they are sequentially presented with concept boards for each climate engineering approach. Respondents evaluate all six climate engineering approaches individually by selecting from the pre-determined list of 12 attributes

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[2] Internet access across the four samples is as follows: 90% in the United Kingdom (Office for National Statistics 2018), 84% in the United States (Ryan and Lewis 2017), 86% in Australia (Australia Bureau of Statistics 2017), and 94% in New Zealand (Díaz Andrade et al. 2018).

confirmed in the qualitative phase of research. The presentation order of concepts and attributes is randomised to avoid order effects. Additional questionnaire items are included to supplement the principal analysis of respondents' attribute associations, including support for small scale trials, understanding of concept boards, ecological views, and prior knowledge of the climate engineering approaches (see Table 13 for question wording). The survey concludes with demographic items.

Measures

Attribute associations

Public perceptions are measured from the count of attribute associations elicited from individual participants for each climate engineering approach. Responses are measured using a free choice, pick-any format and each attribute is coded as '1 = selected' or '0 = not selected' for each approach (see Table 12 for question wording). Modelling mental associations using a binary variable is a requirement of the current method and is appropriate as an association can either exist or not exist in memory (Romaniuk, 2013). Measuring attribute associations in this manner also has significant advantages over traditional attitudinal scales that are prone to 'non-attitude' responses. Rather than measuring fabricated non-attitudes, the current method relies on pre-existing memory associations. Where a respondent has no attitudes toward a climate engineering approach, the attribute selection task would yield few attribute associations compared to respondents with strong attitudes. In contrast, attitudinal scales fail to differentiate between non-attitudes and genuine responses and give each response equal weight in subsequent analysis. Consequently, attribute association measures are comparatively less prone to bias from non-attitude responding.

Following diagnostic tests (Table 14) the final list of attributes is reduced to 10 to avoid duplicate measurement from overlapping attributes (Romaniuk, 2013). The final attribute list maintains a balance of five positive and five negative attributes. To enable further analysis a net positive variable is calculated as the sum of each respondents' positive attribute associations minus the sum of their negative attribute associations for each approach. The principal analysis involves aggregating the net positive variable by individual technique, by CDR techniques, by SRM techniques, or over all six climate engineering techniques to make each relevant comparison. To enable comparisons between samples of different sizes, the net positive value is converted into a percentage where appropriate.

The statistical properties of the net positive variable are examined using aggregation by respondent. The overall net positive variable can take any value between -30 and 30 where '0' represents net-zero positive associations (mean ranging from -3.28 to -4.86 across all countries, standard deviation ranging from 6.43 to 7.19). Graphical analysis shows a close approximation to the normal distribution in all four countries (Figure 5 and Figure 6) and kurtosis and skewness are also acceptable (Table 15) indicating the net positive variable is suitable for further analysis using standard statistical methods.

Univariate tests of associations between the net positive variable and demographic variables identify statistically significant relationships with Age and Political Party variables (see section 2.3.3 and Table 16). However, multivariate analysis does not reveal any significant effect of demographics on the net positive variable once 2-way interactions and Bonferroni corrections are considered (Table 17). Therefore, neither Age nor Political Party are deemed necessary as covariates for the principal analyses.

Understanding

To check the adequacy of the concept boards, respondents are asked whether they could explain each approach to someone else using a five-point Likert-style scale (see Table 12 for question wording) where 1 = Strongly agree and 5 = Strongly disagree (mean ranges from 2.68 to 2.88 across technologies, standard deviation ranges from 0.99 to 1.03). Results show similar satisfactory levels of understanding to the 2012 study: 34–48% indicating they could explain the concept to someone else, 32–41% are neutral, and only 16–27% disagree.

Support for small-scale trials

For each technique, participants are asked to indicate their support for small scale trials on a five-point Likert-style scale (see Table 12 for question wording) where 1 = Strongly agree and 5 = Strongly disagree (mean ranges from 2.71 to 3.25 across technologies, standard deviation ranges from 1.05 to 1.10). The subject of small-scale trials reflects the current state of climate engineering R&D where computer modelling research is already underway and the potential progression to outdoor trials will likely become a matter of public concern.

Prior awareness

Following the concept evaluations, respondents are asked "Did you know about any of these proposals before you began this survey?". Responses are coded as '0 = no' or '1 = yes' (mean ranges from 0.14 to 0.18 across countries, standard deviation ranges from 0.34 to 0.38).

Ecological views

Ecological views are measured using five items from the New Ecological Paradigm (NEP) scale (Dunlap, Van Liere, Mertig, & Jones, 2000). Prior public perception studies yield either mixed or non-significant relationships between NEP items and support for different climate engineering technologies (Braun, Merk, et al., 2018; Braun, Rehdanz, et al., 2018; Dütschke et al., 2016; Merk, Poenitzsch, Kniebes, Rehdanz, & Schmidt, 2015; Merk & Pönitzsch, 2017). Responses are recorded using a five-point Likert-style scale where 1 = Strongly agree and 5 = Strongly disagree. Three items are worded so that agreement indicates a pro-ecological orientation, whereas agreement with the other two items indicate an anti-ecological orientation (see Table 13 for question wording). All items are recoded for analysis so that 1 = Strongly pro-ecological and 5 = Strongly anti-ecological.

Factor analysis using principal component analysis with varimax rotation identifies three positively worded items that load heavily on one factor accounting for 37.5 - 40.2% of the total variation, whereas the negatively worded items load on a separate factor. The scale is therefore reduced to the three positively worded items (Cronbach's α ranging from 0.679 to 0.727 across countries, average 0.715) and aggregated to form an overall NEP score where 15 represents strongly anti-ecological views and 3 represents strongly pro-ecological views (mean ranging from 5.73 to 6.56 across countries; standard deviation ranging from 2.14 to 2.53). The distribution of this variable is approximately normal in all four countries (skewness ranging from 0.69 to 0.87 across countries; kurtosis ranging from 0.37 to 1.27), so bivariate correlations are used to assess the relationship between the NEP variable and net positive association variables.

Comparisons between Samples

Differences between countries in the CDR and SRM net positive variables are assessed using ANOVA (Table 18). A Levene test indicates heterogeneous variance between samples, although the ratios of variance between samples are less than 1.5, indicating the ANOVA is still appropriate. We also test for shifts in public perceptions over time by comparing AU and NZ samples from the current 2018 study against those collected in 2012 by Wright et al. (2014). Due to the replacement of *Biochar* with *BECCS*, we test for differences in the net positive variables for *DACCS, EW, MCB, MIS* and *SAI* using independent sample *t*-tests.

Construction of Concept Maps

To explore the nuanced differences in public perceptions between climate engineering approaches, a concept map for each approach is developed through a chi-square calculation of expected cell counts for each attribute (see Table 19), calculation of percentage skews (deviations) between actual counts and expected values (see Table 20), and then reporting of skews in graphical format (see Figures 7-10 for concept maps of all approaches for each country). To further explore the rationale behind the perceived differences between approaches the absolute values of attribute skews are averaged across the six approaches to produce the mean skew per attribute (see Table 20).

2.3. Results

2.3.1. Public awareness

Despite strong arguments for early public deliberation and increasing availability of information, the public continue to demonstrate little knowledge of climate engineering approaches (Cummings et al., 2017; Wright et al., 2014). In 2012, respondents in AU and NZ surveys were asked whether they had prior knowledge of climate engineering approaches. Only 18% of the AU and NZ respondents acknowledged some awareness of these techniques (Wright et al., 2014). In the 2018 survey the same question found only 18% (UK), 16% (USA), 14% (AU) and 15% (NZ) of respondents reported prior knowledge of the climate engineering approaches tested (95% confidence intervals are plus or minus 1.2 to 1.4 percentage points).

2.3.2. Attribute popularity

Attribute popularity (salience) is measured as each attribute's share of all associations for that country. Although there are substantial variations in share of associations between attributes, there are negligible differences in shares of associations between countries or between years (Table 4). The shares of associations show remarkable consistency with correlations of no less than $r = 0.99$ between countries (within each year) and $r = 0.98$ between years (within AU and NZ).

Of the ten attributes analysed, the most frequently chosen by respondents are the three negative attributes *unknown effects, risky,* and *artificial.* In AU and NZ these three attributes demonstrate little change from 2012 and still account for just over 50% of all associations. When the same data are aggregated by climate engineering approaches they yield a count of associations for each approach, together with the 'net positive' expressed as the total associations for that approach. This calculation of a 'net positive' variable enables the public perceptions of the six approaches to be ranked on that variable (Table 5).

Table 4: Attribute popularity (salience) for climate engineering approaches, as % of country associations

Rank	Attribute	UK 2018	US 2018	AU 2018	NZ 2018	AU 2012	NZ 2012
1	Unknown effects	22	24	24	24	24	25
2	Risky	17	19	19	18	16	16
3	Artificial	13	12	13	14	12	13
4	Understandable	9	7	7	8	8	7
5	Environmentally friendly	8	8	8	7	8	9
6	Controllable	8	7	7	7	7	8
7	Long-term sustainability	7	7	7	7	7	7
8	Quick-fix	6	6	6	6	7	6
9	Eyesore	5	5	5	6	6	6
10	Cost effective	5	5	5	4	5	3

Table 5: Memory associations for climate engineering approaches as counts and as % net positive associations

	Bioenergy with Carbon Capture and Storage	**Direct Air Capture and Carbon Storage**	**Enhanced Weathering**	**Marine Cloud Brightening**	**Mirrors in Space**	**Stratospheric Aerosol Injection**	**Total**
Count of associations (2018)							
United Kingdom (n=751)	1529	1513	1537	1449	1527	1507	9062
United States (n=746)	1456	1418	1481	1424	1535	1503	8817
Australia (n=763)	1618	1664	1606	1597	1670	1696	9851
New Zealand (n=729)	1683	1705	1628	1689	1692	1725	10122
Net positive associations (2018)							
United Kingdom	4%	-8%	-11%	-39%	-48%	-62%	-27%
United States	-9%	-13%	-23%	-41%	-41%	-59%	-31%
Australia	-6%	-13%	-22%	-52%	-53%	-62%	-35%
New Zealand	-1%	-18%	-22%	-44%	-58%	-66%	-35%
Net positive associations (2012)	**(Biochar)**						
Australia	-4%	-13%	-26%	-49%	-59%	-54%	-34%
New Zealand	3%	-16%	-32%	-57%	-73%	-70%	-40%

BECCS replaces *Biochar* as the least negatively perceived approach, whereas *Stratospheric Aerosol Injection*, overtakes *Mirrors in Space* as the most negatively perceived approach. Remarkably, net positive associations for all six approaches show little variation between countries and only minor changes over time. They remain broadly negative, although CDR approaches continue to be perceived less negatively than SRM approaches.

2.3.3. Variables influencing public perceptions

Demographics

Demographic effects on the net positive variable were examined both individually, through univariate tests (Table 16), and jointly through multivariate tests that included 2-way interactions (Table 17) to investigate whether demographic characteristics influence individuals' evaluations of climate engineering. Univariate tests reveal statistically significant relationships between the net positive variable and Age and Political Party variables. Age is recorded as year-born and coded in reverse to give the intuitive interpretation of increasing numbers being equivalent to increasing age, indicating older people tend to be more negative about climate engineering than younger people; however, the effect is small as indicated by r-values of less than 0.30. Turning to consider political party affiliation, Republicans in the US are more negative towards climate engineering than Democrats. A significant relationship is also found for in Australia, UK and NZ where respondents who selected 'Other (*Please Specify):*' were more negative about climate engineering; however, several of these respondents did not provide a clear affiliation (e.g., "none", "I don't know", "prefer not to say"). As noted earlier, multivariate analysis does not reveal any significant effect of demographics on the net positive variable once 2-way interactions and Bonferroni corrections are considered.

Ecological Views

For CDR proposals, pro-ecological views are significantly correlated with less negative net associations in UK $r = 0.142$, ($p < .001$), US $r = 0.168$, ($p < .001$), and NZ $r = 0.117$, ($p = .002$). In contrast, for SRM proposals, pro-ecological views are significantly correlated with more negative net associations in UK r = -0.103, (p = .005) and AU r = -0.095, (p = .009). These results suggest ecological views influence public perceptions of climate engineering and support the proposition that the interaction between ecological and technological views are nuanced and not diametrically opposed (Scarrow 2019). Increasing pro-ecological views among the public may further increase support for CDR and reduce support for SRM. However, caution is needed when interpreting these findings as ecological attitudes are known to be poor predictors of actual behaviour (Wright & Klÿn, 1998).

2.3.4. Differences between samples

We test for differences in perceptions of CDR and SRM proposals between countries with ANOVA and a Games Howell post hoc test (Table 18). The analysis reveals the UK sample is slightly less negative towards CDR approaches than the US, AU, and NZ samples ($F_{3,2985}$ = 3.659, p = .012). Similarly, the UK and US samples were both slightly less negative towards SRM approaches than the AU and NZ samples ($F_{3,2985}$ = 13.464, p < .001). Although these differences are significant, they are not substantial (see Figure 1).

Considering other changes from the 2012 data, in 2018 NZ public perceptions are somewhat less negative towards *EW* (t = -2.973, p = .003), *MCB* (t = -5.615, p < .001), *SAI* (t = -4.202, p < .001) and *MIS* (t = -6.685, p < .001), and AU public perceptions showed no significant differences between years based on a Bonferroni-corrected critical p value of .01. The net positive associations for climate engineering approaches show remarkable consistency, with correlations ranging from r = 0.96 to r = 0.99 between countries (within each year), and r=.98 between years (for AU and NZ).

Figure 1 provides a graphical representation of the 2012 and 2018 data. Although all four countries are economically developed anglophone democracies, they retain substantial geographic, cultural, political, and economic differences, and so the similarity in public perceptions is striking.

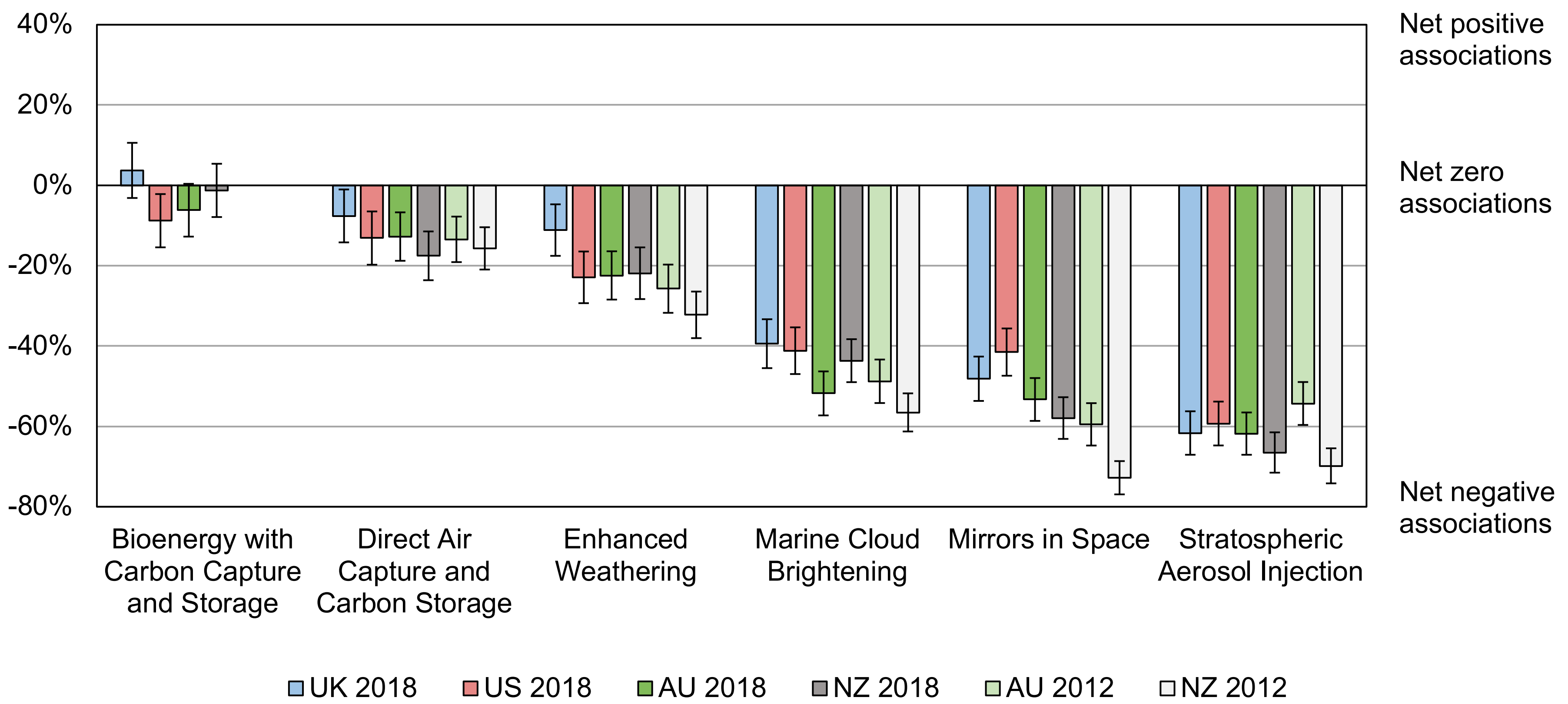


Figure 1: Net positive memory associations for climate engineering approaches. *The bar chart shows that public perceptions of climate engineering proposals are negative, although less so for CDR than SRM. For each proposal there is little variation between countries and over time. Error bars show 95% Confidence Intervals.*

2.3.5. Concept maps

Concept maps for each climate engineering approach present the percentage skews (deviations) between actual counts and expected values, for each attribute, in a graphical format. Positive skews show the attribute is strongly associated with the approach. Negative skews show the attribute is weakly associated with the approach. As found in 2012 (Wright et al., 2014) the concept maps vary considerably between approaches yet are similar between countries (see Figure 2 for UK concept map and Figures 7-10 for other countries).

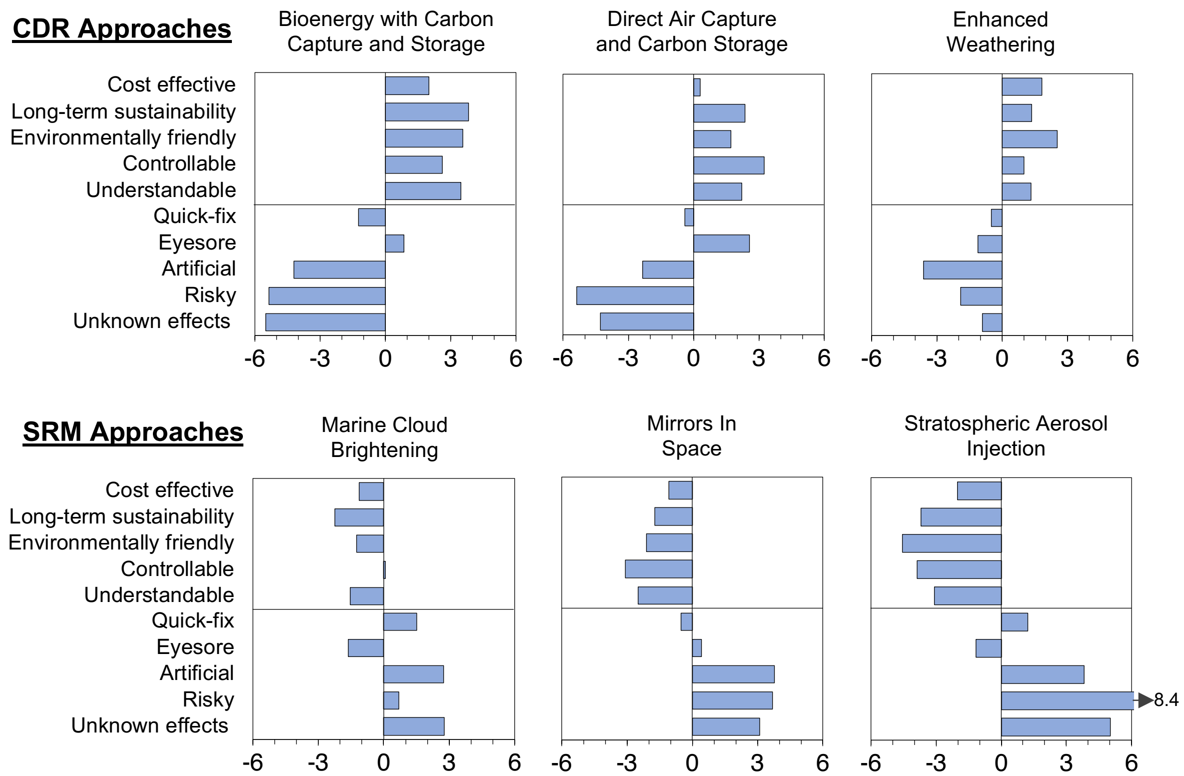


Figure 2: Concept maps for climate engineering approaches in the UK *show the percentage point deviations from expected attribute counts. CDR approaches skew toward more positive attributes (top row panels), whereas SRM approaches skew toward more negative attributes (bottom row panels).*

The concept maps present attributes in inverse order of popularity with positive attributes at the top. CDR approaches skew towards the positive attributes (top row panels) whereas SRM approaches skew towards the negative attributes (bottom row panels). The sources of the overall skew can be understood by examining skews for the individual attributes (see Table 20 for the UK example). The attributes contributing most towards negative skews are *unknown effects*, *risky* and *artificial*. The attributes contributing most to positive skews are *environmentally friendly*, *controllable,* and *long-term sustainability.* Overall, these results show that public perceptions of climate engineering approaches continue to be negative, are very similar between the countries examined, and that CDR approaches continue to be perceived substantially less negatively than SRM approaches. Commercial branding theory indicates that substitutable brands competing within a product category tend to have highly similar rankings of attribute associations; as CDR and SRM have highly dissimilar rankings they may be perceived as different categories, or as non-substitutable activities as far as these respondents are concerned (Romaniuk, 2013). Branding theory also posits that brands with distinctive images receive more attention than brands with indistinct images (Romaniuk, 2013); we therefore conclude that *BECCS* and *DACCS* with distinctively and positively skewed concept maps are likely to receive the most positive public reaction, *SAI* and *MIS* with distinctively and negatively skewed concept maps are likely to receive the most negative public reaction, whereas *EW* and *MCB* with more indistinct and minor skews in their concept maps are likely to generate more subdued public reactions.

2.3.6. Support for trials

Beyond perceptions of climate engineering, we also assess support for further small-scale trials for each approach. Support is measured using a five-point scale with 1 = Strongly Agree and 5 = Strongly Disagree and is combined across countries. Responses are aggregated into agree, neutral and disagree categories for reporting (Table 6). The results show mixed support for small-scale trials of individual approaches with slightly higher support for CDR trials than SRM. The final column demonstrates that the variation in average agreement for small scale trials closely follows the variation in average net positive associations for each approach.

Table 6: Support for small scale trials 2018

	Average (1=Strongly Agree)	Agree (%)	Neutral (%)	Disagree (%)	Average Net Positive Associations (%)
Bioenergy with Carbon Capture and Storage	2.7	45	33	21	-3
Direct Air Capture with Carbon Storage	2.7	45	35	21	-13
Enhanced Weathering	2.8	41	34	25	-19
Marine Cloud Brightening	3.0	33	36	32	-44
Mirrors in Space	3.1	30	35	35	-52
Stratospheric Aerosol Injection	3.3	24	34	41	-62

2.4. Discussion

Despite careful consideration of concerns about climate engineering frames and revising the content of the concept presentations to reflect new scientific knowledge, the net positive associations for the five climate engineering approaches of *DACCS*, *EW, MCB, SAI* and *MIS* are remarkably similar between countries in 2018 as well as between years for AU and NZ. The consistency of these results provides strong evidence that our quantitative approach to measuring public perceptions is robust. The similarities between the 2012 and 2018 measurements also indicate that where framing effects or non-attitude responding may have impacted on public evaluations, the magnitude of impact is unlikely to substantially shift overall evaluations. Nonetheless, it is important that future work continues to track public opinion as more information emerges in the public sphere and awareness of climate engineering becomes widespread. Continued inquiry using experimental designs is also needed to explore antecedents to public opinion on climate engineering and estimate how public perceptions will develop over time.

Several researchers have raised concern that broadly categorising heterogeneous CDR and SRM technologies under the banner of climate engineering is ineffective for informing policy discussions (Minx et al., 2018) and that higher risk perceptions of SRM technologies may undermine the pursuit of CDR technologies (Colvin et al., 2019). Although perceptions of all six climate engineering techniques are predominantly negative, the substantial difference in perceptions between CDR and SRM techniques suggest that citizens do indeed perceive the two groups of technologies as conceptually distinct categories. As in the original 2012 study, we conclude that SRM technologies continue to yield comparatively negative perceptual evaluations and are more likely to elicit more negative public reactions than CDR technologies (Wright et al., 2014). The perceived polarisation provides further justification to separate CDR and SRM as distinct classes of action for addressing climate change.

Another viewpoint argues that it is important to facilitate a nuanced discussion on individual technologies to avoid broad generalisations across heterogeneous technologies (Colvin et al., 2019). Considering the concept maps of six individual technologies (see Figure 2 for UK concept map and Figures 7-10 for other countries) there are clear differences in public perceptions between individual technologies within the CDR and SRM categories. The consistency of these differences across samples demonstrate that public perceptions of climate engineering are technology specific and nuanced. A prime example is the difference in perceptions between *MCB* and *SAI*. Though both technologies fall under the category of SRM, *MCB* elicits substantially fewer negative associations than *SAI* with a difference in net positive associations of between 10 – 23 percentage points across the four 2018 samples (see Table 5). There is a risk that painting perceptions of SRM (or CDR) as broadly negative overlooks nuanced differences between individual technologies and could hinder their future development. These findings further evidence the importance of differentiating between climate engineering technologies at the individual level (Colvin et al., 2019).

Though technical understanding of climate engineering technologies has advanced, media coverage has increased (Doyle, 2017; Watts, 2018), and methods of public engagement are continually refined, it is clear from consistently low public awareness that current attempts at public engagement are insufficient to facilitate global discourse. A potential reason for this is the concerted effort of social scientists to move away from the deficit model of science communication toward consultative and participative mechanisms of public engagement. Indeed, the deficit model is widely discredited on the grounds that public communication mechanisms are ineffective at shifting public perceptions (Corner & Pidgeon, 2010). However, coordinated public communication mechanisms need not be considered a retreat toward deficit ideals if the messages are aimed at communicating objective information to increase public awareness, rather than aiming to influence public perceptions. Commercial branding theory suggests consumers rarely consider brands they are unfamiliar with (Sharp, 2010) likewise, citizens are unlikely to deliberate on emerging scientific concepts they are unaware of. If a large portion of the population are excluded from climate engineering discourses due to low awareness, then the current process of public engagement can hardly be considered democratic. Increasing information on climate engineering in the public sphere would facilitate broader public discourse on the matter outside the context of structured engagement activities. By this reasoning, communicative mechanisms of public engagement still offer some value as a tool for building public awareness.

As the growing necessity for solutions to climate change continues to drive research and development of climate engineering technologies, public engagement efforts need to expand rapidly across global publics. Consultative mechanisms of public engagement, such as the current study, provide excellent tools for eliciting and comparing diverse perspectives at a global scale as well as tracking shifts in public perceptions over time. Likewise, the growth of information communication technologies also presents opportunities to administer web-based or virtual participative mechanisms across global audiences. Regardless of the mechanism, it is important that public engagement occurs sufficiently early to allow public perceptions and concerns to influence the development of climate engineering technologies prior to significant technological development and lock-in.

Since 2012, climate engineering approaches have received increasing attention in international forums. There is more information available in the public domain and the mainstream print media and increased and regular discussion in the context of the Paris Climate Agreement targets. Yet our results show that public knowledge of climate engineering approaches remains low with only small differences in public perceptions between countries and over time. Factors, including age, political affiliation, and pro-ecological views, yield mixed associations with climate engineering perceptions. However, further studies are needed to observe whether these factors remain significant as climate engineering discourse develops.

Perceptions of climate engineering are increasingly relevant following the cancellation of the SPICE experiment and as momentum builds behind the SCoPEx project. Perceptions of SAI are overwhelmingly negative and less than a quarter of respondents support small-scale trials. Though the aerosol particles released through SCoPEx are relatively benign and inconsequential, there is a risk of backlash from an uninformed public toward what might be perceived as initial attempts at SAI deployment.

Even with growing warnings of the need for urgency in climate responses, and greater knowledge of potential large-scale impacts of climate change, our fresh measurement of public engagement with climate engineering approaches show that perceptions are largely unchanged from 2012. Concerns that public discussion of climate engineering could reduce pressure to cut emissions have not been realised, as there are no substantive changes to public knowledge in this area. The climate science community and policymakers can still structure public debate on these novel scientific concepts. The increasingly urgent question is how best to use this opportunity for initial engagement with the public, given the extreme challenges presented by anthropogenic induced global warming and the associated threats to environmentally sustainable futures as partially addressed by the Paris Agreement targets.

2.5. Supplementary information

This supplementary information provides tabular and graphical details of method that are omitted from the main manuscript for reasons of space, as well as additional materials to enable replication by other researchers. The supplementary information is divided into six sections:

2.6.1 Qualitative Phase – Sample Composition

2.6.2 Quantitative Phase – Sample Composition

2.6.3 Quantitative Phase – Materials & Method

2.6.4 Quantitative Phase – Analysis of Net Positive Variable

2.6.5 Quantitative Phase – Comparisons between Samples

2.6.6 Quantitative Phase – Construction of Concept Maps

2.5.1. Qualitative phase – Sample composition

Table 7: New Zealand qualitative demographics (*n*=15)

Subject	Gender	Age	Occupation
1	Male	22	Architectural Draftsman
2	Female	22	Student
3	Male	22	Stunt Performer
4	Female	57	Administration
5	Male	55	Financial Advisor
6	Female	30	Post-Doctoral Fellow
7	Female	25	Sales Representative
8	Female	25	Marketing/Events
9	Male	47	Unemployed
10	Female	21	Rural Consultant
11	Female	54	School Administrator
12	Female	55	School Administrator
13	Male	63	University Academic
14	Male	29	Accommodation Manager
15	Male	27	Student

2.5.2. Quantitative phase – Sample composition

Tables 8-11 report the demographic breakdown of the quantitative samples along with comparative census data or similar independent population estimates for gender, age, and political support. In all four quantitative samples participants are broadly spread across demographic groups, with slight under-representation of under 25-year-olds and irregular slight over-representation of over 65-year-old age groups in the UK, US, AU, and NZ samples. The UK sample shows a slight over-representation of the lowest income level and NZ shows slight under-representation of some lower incomes as well as slight over-representation of some higher incomes. Political party support is slightly under-estimated for the Democrats in the US and National in NZ. The sample characteristics for each country nonetheless show a satisfactory spread of demographics with overall only small deviations from census data or similar independent population estimates. The sample composition is acceptable for the purposes of this research.

Table 8: UK demographics

	UK Sample (*n*=751)	UK Census[1,2]
Age (Years)*	%	%
18 - 24	3	13
25 - 34	16	18
35 - 44	19	19
45 - 54	17	19
55 - 64	18	16
65 - 74	15	12
75 - 80	13	5
Gender		
Male	50	49
Female	50	51
	UK Sample (*n*=751)	**Office for National Statistics (2018)[3]**
Household Annual Income (GBP£)		
Less than £12,999	16	6
£13,000-£18,999	9	11
£19,000-£25,999	14	16
£26,000-£31,999	15	13
£32,000-£47,999	23	26
£48,000-£63,999	11	13
£64,000-£95,999	7	11
More than £96,000	4	5
	UK Sample (*n*=751)	**YouGov (Nov, 2018)[4]**
Political Support**		
Conservative Party	40	39
Labour Party	32	36
Liberal Democrats	10	8
Other/Independent	17	14
Education		
Completed Postgraduate (e.g., Masters or PhD)	8	
Completed undergraduate (e.g., Bachelor's Degree)	27	
Some tertiary education (e.g., Certificate or Diploma)	17	
Trade or Technical Qualification (e.g., Apprenticeship, Industry Qualification, etc.)	15	
Graduated Secondary School (High School)	30	
Graduated Primary School (Elementary School)	3	
Location		
More than 5 million people (Major Urban Area)	8	
1 million to 4.9 million people	5	
100,000 to 999,999 people	17	
50,000 to 99,999 people	16	
10,000 to 49,999 people	23	
1,000 to 9,999 people	20	
200 to 999 people	7	
Less than 200 people (Rural Area)	4	

*Census data for age is calculated as the proportion of the 18 - 80 age group.
**Political support is calculated excluding invalid responses.

Table 9: US demographics

	US Sample (*n*=746)	Annual Estimates of the Resident Population (2017)[5]
Age (Years)*	%	%
18 - 24	4	13
25 - 34	14	19
35 - 44	19	17
45 - 54	17	18
55 - 64	18	17
65 - 74	16	12
75 - 80	13	4
Gender		
Male	49	49
Female	51	51
	US Sample (*n*=746)	**Current Population Survey (2017)[6]**
Household Annual Income (USD$)		
Less than $10,000	8	4
$10,000 to $19,999	8	5
$20,000 to $29,999	10	8
$30,000 to $39,999	9	8
$40,000 to $49,999	9	8
$50,000 to $59,999	7	7
$60,000 to $69,999	8	7
$70,000 to $99,999	18	17
$100,000 to $149,999	15	17
$150,000 to $199,999	3	9
More than $200,000	4	10
	US Sample (*n*=746)	**SRSS (October 2018)[7]**
Political Support**		
Republican Party	45	42
Democratic Party	49	56
Other/Independent	6	2
Education		
Completed Postgraduate (e.g., Masters or PhD)	19	
Completed undergraduate (e.g., Bachelor's Degree)	29	
Some tertiary education (e.g., Certificate or Diploma)	17	
Trade or Technical Qualification (e.g., Apprenticeship, Industry Qualification, etc.)	9	
Graduated Secondary School (High School)	23	
Graduated Primary School (Elementary School)	2	
Location		
More than 5 million people (Major Urban Area)	5	
1 million to 4.9 million people	11	
100,000 to 999,999 people	17	
50,000 to 99,999 people	16	
10,000 to 49,999 people	21	
1,000 to 9,999 people	10	
200 to 999 people	8	
Less than 200 people (Rural Area)	11	

*Data for age is calculated as the proportion of the 18 - 80 age group.
**Political support is calculated excluding invalid responses.

Table 10: Australian demographics

	AU Sample (*n*=763)	AU Census[8]
Age (Years)*	%	%
18 - 24	5	12
25 - 34	13	19
35 - 44	20	18
45 - 54	16	18
55 - 64	20	16
65 - 74	25	12
75 - 80	4	4
Gender		
Male	48	49
Female	52	51
Household Weekly Income (AUSD$)		
Less than $149	4	3
$150-$299	4	3
$300-$399	5	4
$400-$499	8	9
$500-$649	10	6
$650-$799	8	9
$800-$999	9	9
$1,000-$1,249	12	11
$1,250-$1,499	9	10
$1,500-$1,749	8	8
$1,750-$1,999	6	7
$2,000-$2,999	10	14
More than $3,000	9	9
	AU Sample (*n*=763)	**Essential Research (December 2018)[9]**
Political Support**		
Australian Labour Party	43	39
Liberal Party of Australia	33	34
National Party of Australia	7	4
Pauline Hanson's One Nation	5	6
Australian Greens	6	10
Independent/Other	7	7
Education		
Completed Postgraduate (e.g., Masters or PhD)	9	
Completed undergraduate (e.g., Bachelor's Degree)	23	
Some tertiary education (e.g., Certificate or Diploma)	25	
Trade or Technical Qualification (e.g., Apprenticeship, Industry Qualification, etc.)	12	
Graduated Secondary School (High School)	27	
Graduated Primary School (Elementary School)	4	
Location		
More than 5 million people (Major Urban Area)	17	
1 million to 4.9 million people	22	
100,000 to 999,999 people	15	
50,000 to 99,999 people	10	
10,000 to 49,999 people	16	
1,000 to 9,999 people	15	
200 to 999 people	3	
Less than 200 people (Rural Area)	3	

*Census data for age is calculated as the proportion of the 18 - 80 age group.
**Political support is calculated excluding invalid responses.

Table 11: NZ demographics

	NZ Sample (*n*=729)	NZ Census[10-13]
Age (Years)*	%	%
18 - 24	6	13
25 - 34	13	17
35 - 44	17	19
45 - 54	17	20
55 - 64	17	16
65 - 74	16	11
75 - 80	14	4
Gender		
Male	50	49
Female	50	51
Household Annual Income (NZD$)		
Less than $10,000	3	20
$10,001 - $20,000	6	18
$20,001 - $30,000	14	14
$30,001 - $40,000	13	12
$40,001 - $50,000	12	10
$50,001 - $60,000	8	7
$60,001 - $70,000	7	6
$70,001 - $100,000	17	8
$100,001 - $150,000	15	4
More than $150,001	6	2
	NZ Sample (*n*=729)	**Colmar Brunton (November 2018)[14]**
Political Support**		
New Zealand National Party	35	46
The New Zealand Labour Party	40	43
Green Party of Aotearoa New Zealand	8	5
New Zealand First	9	4
Other	1	2
Education		
Completed Postgraduate (e.g., Masters or PhD)	10	
Completed undergraduate (e.g., Bachelor's Degree)	25	
Some tertiary education (e.g., Certificate or Diploma)	24	
Trade or Technical Qualification (e.g., Apprenticeship, Industry Qualification, etc.)	13	
Graduated Secondary School (High School)	25	
Graduated Primary School (Elementary School)	4	
Location		
More than 1,000,000 people (Major Urban Area)	23	
100,000 to 999,999 people	22	
30,000 to 99,999 people	18	
10,000 to 29,999 people	14	
1,000 to 9,999 people	13	
200 to 999 people	3	
Less than 200 people (Rural Area)	6	

*Census data for age is calculated as the proportion of the 18 - 80 age group.
**Political support is calculated excluding invalid responses.

Demographic Data Sources

1. https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/2011censuspopulationestimatesbysingleyearofageandsexforlocalauthoritiesintheunitedkingdom
2. https://webarchive.nationalarchives.gov.uk/20160108132257/http://www.ons.gov.uk/ons/dcp171778_292378.pdf
3. https://www.ons.gov.uk/file?uri=/peoplepopulationandcommunity/personalandhouseholdfinances/incomeandwealth/adhocs/009772grosshouseholdincomeukfinancialyearending2018/grossbandedincome1718.xls
4. https://d25d2506sfb94s.cloudfront.net/cumulus_uploads/document/rrlh8uvy0x/TheTimes_181119_VI_Trackers_bpc_w.pdf
5. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?
6. https://www.census.gov/data/tables/time-series/demo/income-poverty/cps-finc.html
7. http://cdn.cnn.com/cnn/2018/images/10/09/rel9b.-.2018.midterms.pdf
8. https://auth.censusdata.abs.gov.au/webapi/jsf/tableView/tableView.xhtml#\
9. https://www.essentialvision.com.au/wp-content/uploads/2018/12/Essential-Report-041218.pdf
10. http://nzdotstat.stats.govt.nz/wbos/Index.aspx?DataSetCode=TABLECODE8001
11. http://archive.stats.govt.nz/Census/2013-census/profile-and-summary-reports/quickstats-about-a-place.aspx?request_value=13067&tabname=
12. http://archive.stats.govt.nz/Census/2013-census/profile-and-summary-reports/quickstats-income.aspx
13. http://archive.stats.govt.nz/~/media/Statistics/Census/2013%20Census/profile-and-summary-reports/quickstats-about-income/quickstats-income-tables.xls
14. https://www.colmarbrunton.co.nz/wp-content/uploads/2018/12/Prelim_24-28-November-2018_1-NEWS-Colmar-Brunton-Poll-report-.pdf

2.5.3. Quantitative phase – Materials & method

Introduction and warmup questions

Figure 3: Survey introduction and concept introduction

Questionnaire page 1. Survey introduction and warm up questions

Global warming refers to the idea that the world's average temperature has been increasing, may increase more in the future, and is causing changes to the world's climate. These changes have been attributed to increasing greenhouse gas emissions such as carbon dioxide.

Please read the statements below and then indicate whether you agree or disagree by clicking
ONE button beside each statement

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Don't know
We should try to reduce global warming.	○	○	○	○	○	○
Global warming is causing changes to the climate.	○	○	○	○	○	○
Humans are primarily responsible for global warming.	○	○	○	○	○	○

→

Questionnaire page 2. Concept introduction

In response to global warming, 196 countries adopted the 2015 Paris Agreement under the United Nations Framework Convention on Climate Change. The aim of the agreement is to limit the global increase in temperatures to below 2° Celsius.

Alongside ways for adapting to global warming, governments and scientists are considering a range of possible solutions for achieving the 2°C goal. Some proposals include reducing global emissions, removing carbon dioxide from the air, or reflecting sunlight back into space.

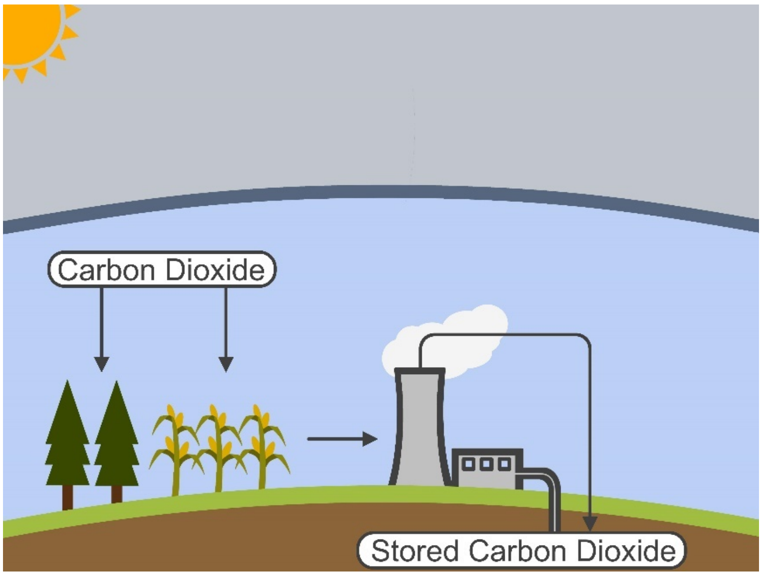
We would like to know what you think about some of these proposals for removing carbon dioxide and reflecting sunlight. In the following pages we will present six proposals and ask some questions about each one. Please read the description and tick the boxes that you think apply. There are no right or wrong answers in this survey. Rather we are interested in your opinion.

→

Concept Boards

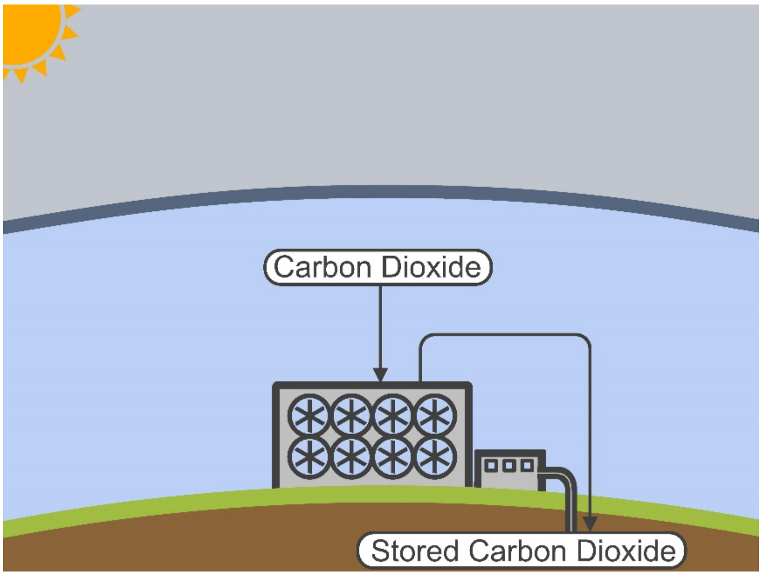
Figure 4: Concept boards

Bio-Energy with Carbon Capture and Storage (BECCS)



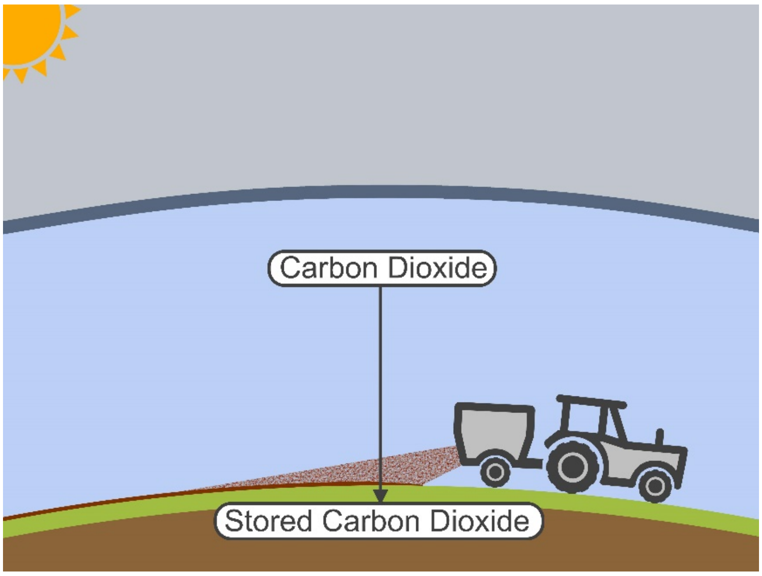
Bio-energy with Carbon Capture and Storage (BECCS) involves growing plants or 'biomass' to remove carbon dioxide from the air. The biomass is combusted to produce renewable energy. The emitted carbon dioxide is captured and stored indefinitely in underground reservoirs. Producing biomass, building infrastructure, and transporting carbon incur costs. The land requirements for BECCS could affect food production, biodiversity, water allocation, and deforestation. Producing and transporting biomass require renewable energy sources to ensure that more carbon dioxide is stored than emitted. BECCS could be introduced gradually, however, large-scale implementation and infrastructure is required to reduce global temperatures.

Direct Air Capture and Carbon Storage (DACCS)



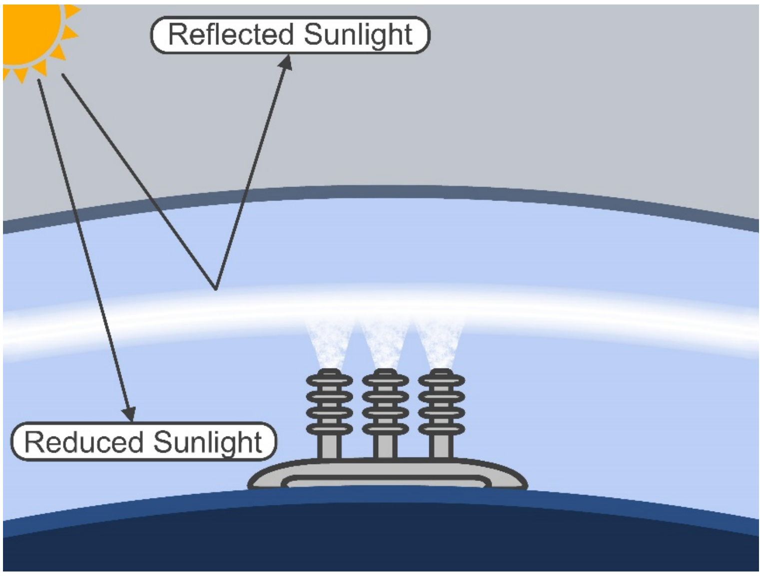
Direct Air Capture and Carbon Storage (DACCS) involves building structures that filter carbon dioxide from the air. Carbon dioxide is captured, transported, and stored indefinitely in underground reservoirs. Structures can be located anywhere and would target areas with suitable underground reservoirs. Building and operating air capture structures requires land and incurs costs. Powering the air capture structures and transporting carbon dioxide requires renewable energy sources to ensure that more carbon is stored than emitted. Direct Air Capture could be introduced gradually, however, large-scale implementation and infrastructure are required to reduce global temperatures.

Enhanced Weathering



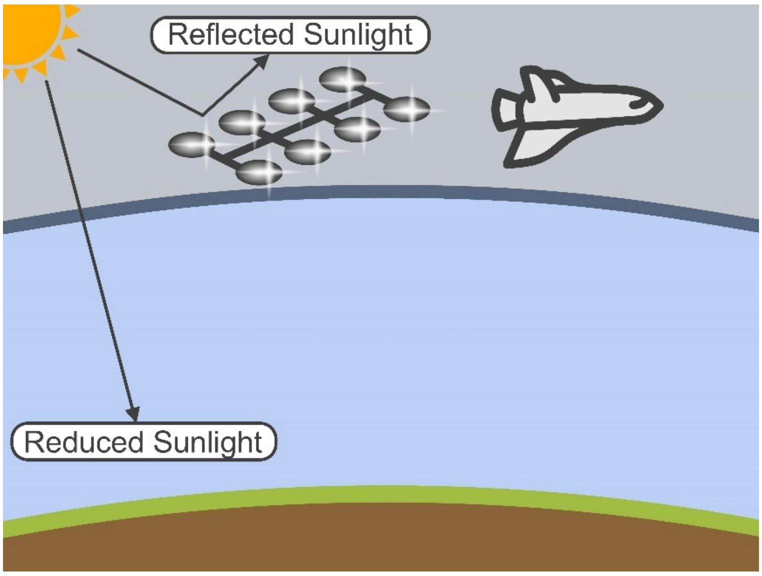
Certain rocks react with atmospheric carbon dioxide to break down or ‘weather’. This reaction forms new minerals that store carbon indefinitely. Crushing and spreading the rocks accelerates carbon dioxide removal, improves soil quality, may reduce mine wastes, and could reduce ocean acidification if washed out to sea. Enhanced Weathering requires land and could affect biodiversity, human health, and leach heavy metals into soils. Mining, transporting, and spreading rocks incur costs and require renewable energy sources to ensure that more carbon is stored than emitted. Enhanced Weathering could be introduced gradually, however, large-scale implementation is required to reduce global temperatures.

Marine Cloud Brightening



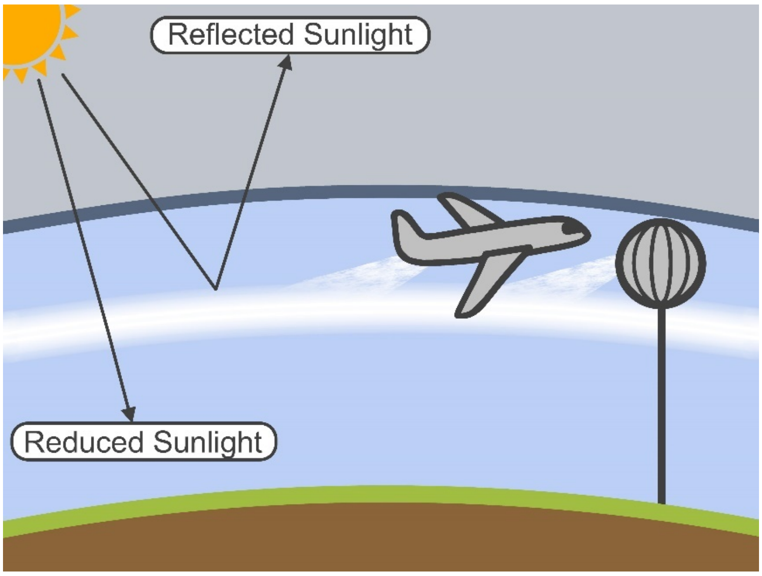
Marine Cloud Brightening involves automated ships spraying small seawater droplets above the ocean in targeted areas. Vapour forms around these droplets, increasing the number and brightness of clouds reflecting some sunlight back into space. Developing and building fleets of spraying vessels incurs costs. Cloud brightening is restricted to marine areas and may alter local rainfall patterns. Changes in light, ocean temperature, and currents may affect marine nutrient growth. Large-scale implementation and continuous applications are required to maintain the cooling effect. Temperatures would quickly revert to pre-application levels if stopped. Implementation may require international agreements.

Mirrors in Space



Mirrors in Space involves positioning reflective structures to orbit the Earth. These structures intercept and reflect some sunlight back into space, rapidly cooling the Earth. Space-craft would be used to position the materials. Space transportation incurs costs and would require large-scale investment, research, and development. Implementation would increase the number of orbital objects and could produce an uneven cooling effect, alter rainfall patterns, and change the appearance of the night sky. Large-scale implementation is required and temperatures would revert to pre-application levels if the structures were removed. Implementation would take decades and may require international agreements.

Stratospheric Aerosol Injection



Stratospheric Aerosol Injection involves spreading tiny reflective particles into the stratosphere. The particles reflect some sunlight back into space, rapidly cooling the whole Earth. Sulphate aerosols could be spread using aeroplanes or large balloons tethered to lightweight pipes. Building fleets of aeroplanes or balloons incurs costs. Stratospheric aerosols would make the sky whiter and could affect the ozone layer, rainfall patterns and crop yields. Environmental and local impacts are poorly understood. Large-scale implementation and continuous applications are required to maintain the cooling effect. Temperatures would quickly revert to pre-application levels if stopped. Implementation may require international agreements.

Concept evaluation

On separated pages respondents evaluate each concept image and description individually in a randomised order (See Figure 4) using the measures outlined below in (Table 12):

Table 12: Concept evaluation questions

Item	Format	Responses
Attribute selection		
Which of the descriptors in the list below do you think applies to [concept name]? Please select as many as apply.	Multiple answer (Pick-any)	Unknown effects; Risky; Artificial; Understandable; Environmentally friendly; Controllable; Long-term sustainability; Quick-fix; Eyesore; Cost effective; Beneficial; Unpredictable [a]
Concept statements		
Please read the statements below and indicate whether you agree or disagree by clicking ONE button beside each statement. [b]	Single answer (Likert-scale)	Strongly agree; Agree; Neutral; Disagree; Strongly disagree
I think [concept name] would help reduce global warming.		
I would support small-scale trials of [concept name].		
After reading the description I think that I could explain [concept name] to somebody else.		

[a] Responses order in the attribute selection task are randomised to reduce order effects.
[b] Item order in the concept statement task is randomised to reduce order effects.

Further questionnaire items

After the concept evaluation block, respondents completed further questionnaire items outlined in Table 13. Then, participants were asked a series of demographic questions outlined in Tables 8-11.

Table 13: Further questionnaire items

Item	Format	Responses
Prior awareness		
Did you know about any of these proposals before you began this survey?	Single Answer (Pick-one)	Yes; No
Ecological concern (NEP scale items)		
Now we would like to ask a few questions about your views on the environment. Please read the statements below and indicate whether you agree or disagree by clicking ONE button beside each statement.	Single answer (Likert-scale)	Strongly agree; Agree; Neutral; Disagree; Strongly disagree
Humans have the right to modify the natural environment to suit their needs.		
Humans are severely abusing the environment.		
We are approaching the limit of the number of people the earth can support		
The balance of nature is very delicate and easily upset.		
Humans will eventually learn enough about how nature works to be able to control it.		

2.5.4. Quantitative phase – Analysis of net positive variable

Elimination of duplicate measures.

Following the procedures used in the 2012 study (Wright et al. 2014), we use Kendal Tau-B nonparametric attribute correlations (Table 14) to detect and eliminate any overlapping memory structures (Romaniuk 2013). The results presented are the average of six correlation matrixes, one for each climate engineering technique, across the four countries. None of the reported correlations are high. However, three correlations are above 0.35 and thus substantially exceed the average for the attributes involved. This meets the criteria for eliminating attributes to avoid duplicate measurement from overlapping attributes (Romaniuk 2013), and as in the 2012 study (Wright et al. 2014), the attributes *unpredictable* and *beneficial* are excluded from analysis.

Table 14: Average Kendall Tau-b nonparametric correlations (n=2989)

	Unk	Unp	Ris	Art	Qui	Eye	Und	Ben	Con	Env	Sus	Cos
Unknown effects		0.36	0.30	0.17	0.01	0.05	-0.13	-0.25	-0.21	-0.23	-0.20	-0.17
Unpredictable*	0.36		0.37	0.20	0.04	0.07	-0.14	-0.25	-0.22	-0.22	-0.20	-0.16
Risky	0.30	0.37		0.21	0.05	0.10	-0.13	-0.24	-0.21	-0.23	-0.18	-0.13
Artificial	0.17	0.20	0.21		0.11	0.14	-0.03	-0.12	-0.06	-0.13	-0.10	-0.07
Quick Fix	0.01	0.04	0.05	0.11		0.06	0.00	-0.02	0.00	-0.03	-0.03	0.02
Eyesore	0.05	0.07	0.10	0.14	0.06		-0.02	-0.07	-0.03	-0.07	-0.05	-0.02
Understandable	-0.13	-0.14	-0.13	-0.03	0.00	-0.02		0.25	0.23	0.23	0.19	0.12
Beneficial*	-0.25	-0.25	-0.24	-0.12	-0.02	-0.07	0.25		0.31	0.35	0.31	0.21
Controllable	-0.21	-0.22	-0.21	-0.06	0.00	-0.03	0.23	0.31		0.28	0.25	0.18
Env. Friendly	-0.23	-0.22	-0.23	-0.13	-0.03	-0.07	0.23	0.35	0.28		0.31	0.21
Sustainability	-0.20	-0.20	-0.18	-0.10	-0.03	-0.05	0.19	0.31	0.25	0.31		0.21
Cost effective	-0.17	-0.16	-0.13	-0.07	0.02	-0.02	0.12	0.21	0.18	0.21	0.21	

*Unpredictable and Beneficial were both correlated with other attributes and were therefore removed.

Statistical properties of net positive variable

For each country, a Kolmogorov-Smirnov test rejects the null hypothesis of no difference from a normal distribution. However graphical analysis does show a close approximation to the normal distribution in all countries as shown by histograms (Figure 5) and Q-Q Plots (Figure 6). Kurtosis of the net positive variable in each country ranges from 0.484 to 0.968 (SE approximately 0.18), while skewness ranges from -0.001 to 0.092 (SE approximately 0.90; Table 15). Although Kurtosis is less than the normal distribution value of 3.0, it is within the range considered acceptable for approximation to a normal distribution. Skewness is not significantly different from zero. The net positive variable is therefore suitable for further analysis using standard statistical tests.

Figure 5: Histogram of net positive measure

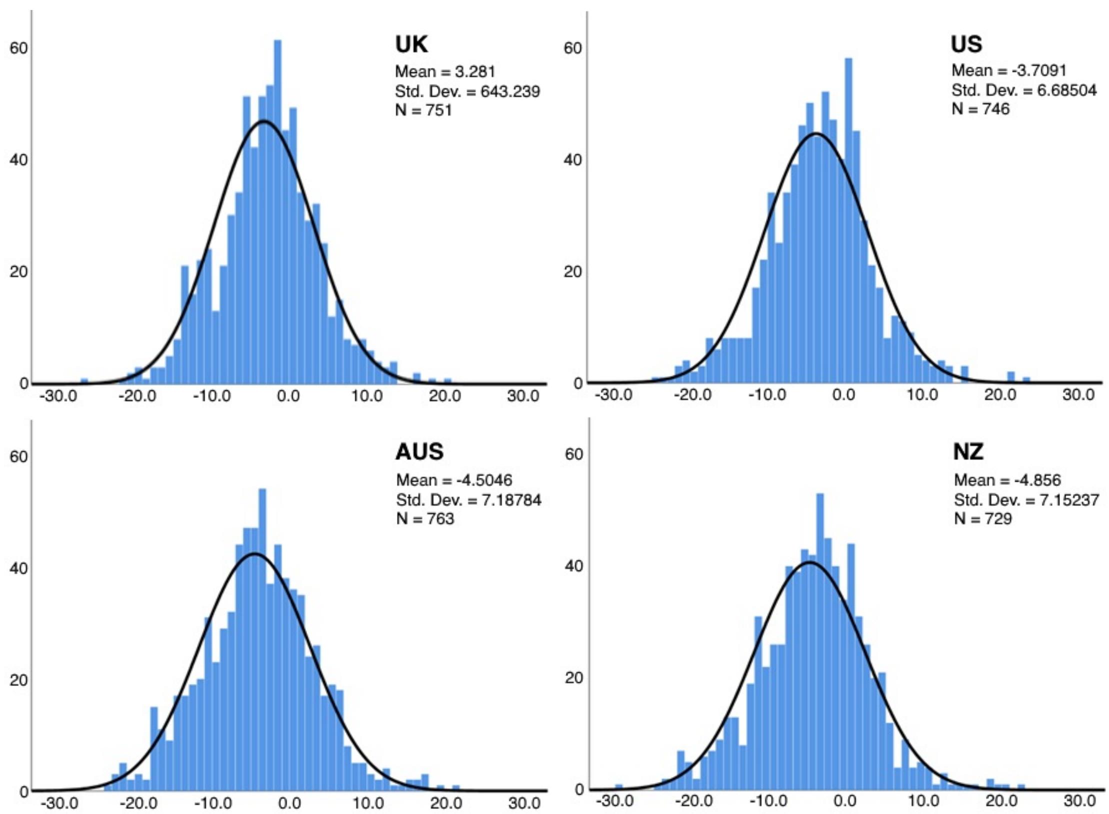


Figure 6: Normal Q-Q plot of net positive measure

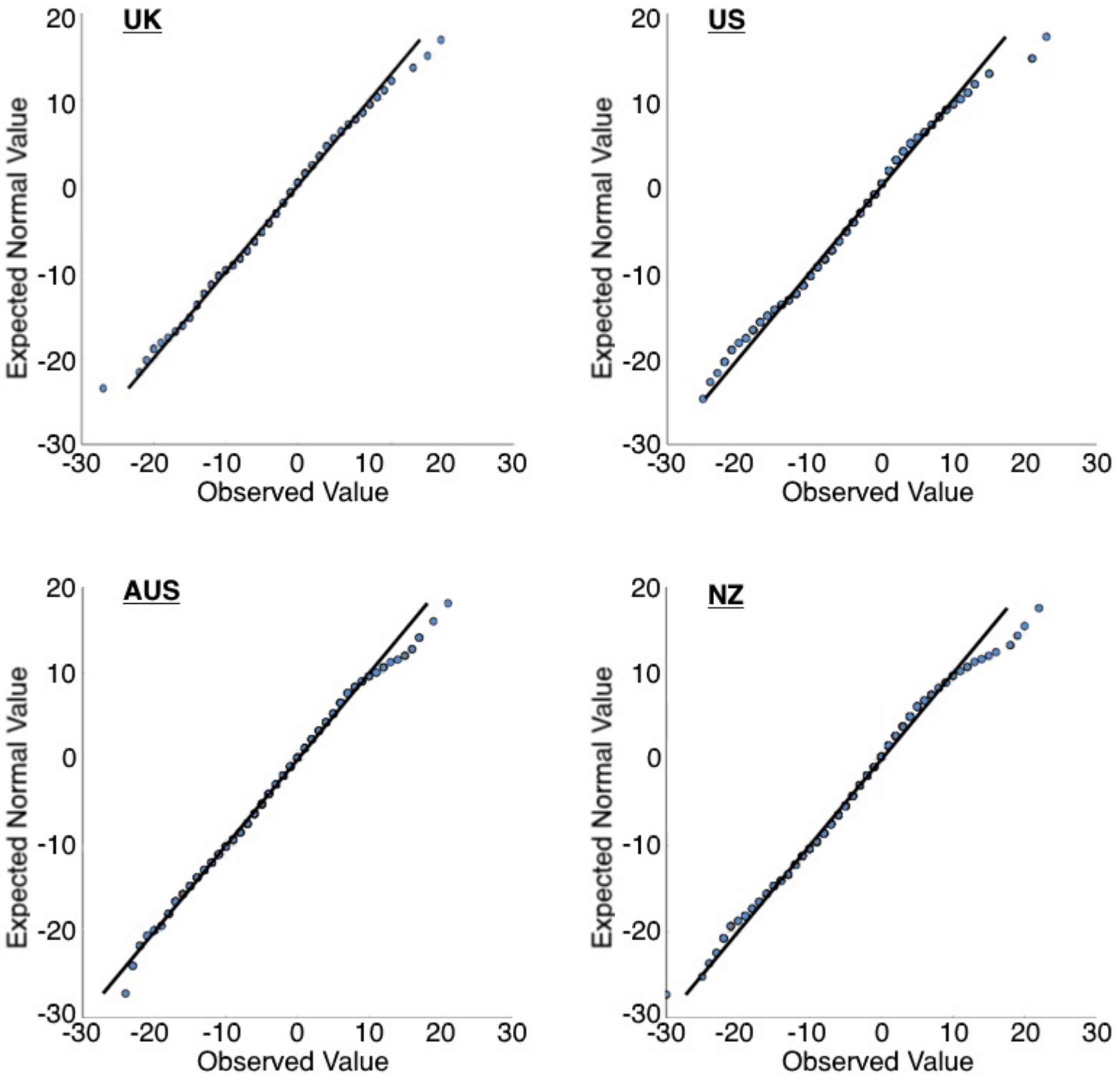


Table 15: Kurtosis and skewness of the net positive variable

Sample	Kurtosis	Standard Error
UK	.484	.178
US	.968	.179
AU	.327	.177
NZ	.789	.181
Sample	**Skewness**	**Standard Error**
UK	.000	.089
US	.015	.090
AU	.092	.089
NZ	-.001	.091

We next consider univariate tests of associations between the net positive variable and demographic variables, including political party affiliation (Table 16). ANOVA is used for all demographic tests except Age, where bivariate correlation is appropriate. Due to the large number of tests, we employ the Bonferroni correction to critical p-values. Statistically significant relationships are found with the Age and Political Party variables in all four countries. Age is recorded as year-born and coded in reverse to give the intuitive interpretation of increasing numbers being equivalent to increasing age, indicating older people tend to be more negative about climate engineering than younger people; however, the effect is small as indicated by r-values of less than 0.30.

Turning to consider political party affiliation, Republicans in the US are more negative towards climate engineering than Democrats. A significant relationship is also found in Australia, UK, and NZ where respondents who selected 'Other (*Please Specify):*' were more negative about climate engineering; however, several of these respondents did not provide a clear affiliation (e.g., "none", "I don't know", "prefer not to say"). A further test for political party excluding the 'Other' category showed no significant relationship in the UK, AU, and NZ, although the association between political party and the net positive variable remained statistically significant in the US. Political party was deemed to be unnecessary as a covariate for the principal analyses.

As univariate tests may be subject to omitted variable bias and do not consider interactions between demographic variables, we extend the analysis by jointly estimating demographic effects and 2-way interactions using a general linear model (Table 17). Again, we use the Bonferroni correction to critical p-values to account for the large number of statistical tests undertaken. The analysis does not reveal any significant effect of demographics on the net positive variable based on a Bonferroni corrected critical P-Value of .002 (Table 17).

Table 16: Univariate tests for differences on the net positive variable

		Test statistic	Test statistic value	P value	Bonferroni-corrected critical P value
UK Data					
Gender	One Way Anova	$\mathbf{F}_{(.05, 1, 749)}$	0.017	0.895	0.008
Location	One Way Anova	$\mathbf{F}_{(.05, 7, 743)}$	1.520	0.157	0.008
Education	One Way Anova	$\mathbf{F}_{(.05, 5, 745)}$	2.357	0.039	0.008
Household Income	One Way Anova	$\mathbf{F}_{(.05, 8, 742)}$	1.682	0.099	0.008
Political Party	One Way Anova	$\mathbf{F}_{(.05, 5, 745)}$	4.746	<0.001	0.008
Age	Correlation	r	-0.138	<0.001	0.008
US Data					
Gender	One Way Anova	$\mathbf{F}_{(.05, 1, 745)}$	3.453	0.064	0.008
Location	One Way Anova	$\mathbf{F}_{(.05, 7, 738)}$	0.754	0.626	0.008
Education	One Way Anova	$\mathbf{F}_{(.05, 5, 740)}$	1.668	0.140	0.008
Household Income	One Way Anova	$\mathbf{F}_{(.05, 10, 735)}$	0.989	0.452	0.008
Political Party	One Way Anova	$\mathbf{F}_{(.05, 2, 739)}$	10.079	<0.001	0.008
Age	Correlation	r	-0.295	<0.001	0.008
AU Data					
Gender	One Way Anova	$\mathbf{F}_{(.05, 1, 761)}$	1.412	0.235	0.008
Location	One Way Anova	$\mathbf{F}_{(.05, 7, 755)}$	1.794	0.085	0.008
Education	One Way Anova	$\mathbf{F}_{(.05, 5, 757)}$	2.001	0.076	0.008
Household Income	One Way Anova	$\mathbf{F}_{(.05, 13, 749)}$	0.818	0.641	0.008
Political Party	One Way Anova	$\mathbf{F}_{(.05, 3, 752)}$	6.417	<0.001	0.008
Age	Correlation	r	-0.286	<0.001	0.008
NZ Data					
Gender	One Way Anova	$\mathbf{F}_{(.05, 1, 727)}$	0.057	0.812	0.008
Location	One Way Anova	$\mathbf{F}_{(.05, 6, 722)}$	1.078	0.374	0.008
Education	One Way Anova	$\mathbf{F}_{(.05, 5, 723)}$	1.329	0.250	0.008
Household Income	One Way Anova	$\mathbf{F}_{(.05, 9, 719)}$	0.387	0.941	0.008
Political Party	One Way Anova	$\mathbf{F}_{(.05, 4, 716)}$	4.357	0.002	0.008
Age	Correlation	r	-0.208	<0.001	0.008

Table 17: Multivariate tests for differences on the net positive variable

	F value	P value	Bonferroni- corrected critical P value*
UK Data			
1 Intercept	0.817	0.369	0.002
2 Gender	0.179	0.673	0.002
3 Location	0.400	0.903	0.002
4 Education	0.573	0.720	0.002
5 Household Income	1.056	0.393	0.002
6 Political Party	1.368	0.236	0.002
7 Age	0.060	0.807	0.002
2×3 Interaction	0.502	0.833	0.002
2×4 Interaction	0.401	0.848	0.002
2×5 Interaction	0.369	0.937	0.002
2×6 Interaction	1.040	0.386	0.002
2×7 Interaction	0.769	0.381	0.002
3×4 Interaction	0.850	0.704	0.002
3×5 Interaction	0.575	0.994	0.002
3×6 Interaction	0.862	0.668	0.002
3×7 Interaction	0.530	0.812	0.002
4×5 Interaction	1.065	0.370	0.002
4×6 Interaction	1.145	0.305	0.002
4×7 Interaction	0.180	0.970	0.002
5×6 Interaction	0.724	0.868	0.002
5×7 Interaction	0.629	0.753	0.002
6×7 Interaction	1.769	0.134	0.002
US Data			
1 Intercept	0.242	0.624	0.002
2 Gender	0.877	0.352	0.002
3 Location	1.070	0.384	0.002
4 Education	0.597	0.702	0.002
5 Household Income	0.866	0.566	0.002
6 Political Party	0.665	0.516	0.002
7 Age	0.396	0.529	0.002
2×3 Interaction	1.062	0.387	0.002
2×4 Interaction	0.651	0.661	0.002
2×5 Interaction	1.038	0.410	0.002
2×6 Interaction	0.558	0.573	0.002
2×7 Interaction	1.304	0.254	0.002
3×4 Interaction	0.902	0.622	0.002
3×5 Interaction	1.246	0.105	0.002
3×6 Interaction	0.855	0.609	0.002
3×7 Interaction	1.488	0.169	0.002
4×5 Interaction	1.367	0.069	0.002
4×6 Interaction	1.608	0.110	0.002
4×7 Interaction	1.239	0.289	0.002
5×6 Interaction	1.252	0.211	0.002
5×7 Interaction	0.459	0.916	0.002
6×7 Interaction	1.265	0.283	0.002

AU Data			
1 Intercept	1.000	0.325	0.002
2 Gender	0.122	0.727	0.002
3 Location	1.739	0.103	0.002
4 Education	2.679	0.022	0.002
5 Household Income	1.081	0.373	0.002
6 Political Party	2.095	0.103	0.002
7 Age	3.351	0.068	0.002
2×3 Interaction	1.981	0.056	0.002
2×4 Interaction	2.536	0.028	0.002
2×5 Interaction	0.948	0.503	0.002
2×6 Interaction	4.195	0.006	0.002
2×7 Interaction	1.840	0.176	0.002
3×4 Interaction	1.100	0.325	0.002
3×5 Interaction	1.181	0.151	0.002
3×6 Interaction	1.121	0.328	0.002
3×7 Interaction	0.911	0.498	0.002
4×5 Interaction	0.829	0.818	0.002
4×6 Interaction	1.681	0.057	0.002
4×7 Interaction	1.696	0.134	0.002
5×6 Interaction	1.099	0.319	0.002
5×7 Interaction	1.272	0.227	0.002
6×7 Interaction	0.978	0.403	0.002
NZ Data			
1 Intercept	17.921	0.060	0.002
2 Gender	0.001	0.976	0.002
3 Location	0.665	0.678	0.002
4 Education	0.639	0.671	0.002
5 Household Income	0.430	0.918	0.002
6 Political Party	1.316	0.269	0.002
7 Age	0.497	0.481	0.002
2×3 Interaction	0.709	0.642	0.002
2×4 Interaction	2.033	0.073	0.002
2×5 Interaction	1.685	0.090	0.002
2×6 Interaction	1.740	0.140	0.002
2×7 Interaction	1.264	0.261	0.002
3×4 Interaction	0.911	0.605	0.002
3×5 Interaction	0.867	0.730	0.002
3×6 Interaction	0.943	0.543	0.002
3×7 Interaction	0.337	0.917	0.002
4×5 Interaction	0.997	0.481	0.002
4×6 Interaction	0.727	0.799	0.002
4×7 Interaction	1.878	0.097	0.002
5×6 Interaction	0.920	0.606	0.002
5×7 Interaction	1.428	0.173	0.002
6×7 Interaction	0.548	0.700	0.002

2.5.5. Quantitative phase – Comparisons between samples

Table 18: Tests for differences of CDR and SRM evaluations between countries

	Test	Test statistic	Test statistic value	P value
Homogeneity of Variance Between Countries				
CDR Net Positive Variable	Levene Statistic[a]	$W_{(.05, 3, 2985)}$	4.157	0.006
SRM Net Positive Variable	Levene Statistic	$W_{(.05, 3, 2985)}$	3.234	0.021
Variance Between Countries				
CDR Net Positive Variable	One Way Anova	$F_{(.05, 3, 2985)}$	3.659	0.012
SRM Net Positive Variable	One Way Anova	$F_{(.05, 3, 2985)}$	13.464	<0.001

	Test	Mean Difference	Std. Error	P value
Post-Hoc Test for Multiple Comparisons (CDR)				
UK[b] x US[c]	Games Howell	0.570	0.211	0.035
UK x AU	Games Howell	0.576	0.217	0.041
UK x NZ	Games Howell	0.622	0.227	0.031
US x AU	Games Howell	0.005	0.211	1.000
US X NZ	Games Howell	0.052	0.221	0.995
AU x NZ	Games Howell	0.047	0.227	0.997
Post-Hoc Test for Multiple Comparisons (SRM)				
UK x US	Games Howell	-0.142	0.194	0.883
UK x AU	Games Howell	0.648	0.200	0.007
UK x NZ	Games Howell	0.953	0.197	<0.001
US x AU	Games Howell	0.790	0.203	0.001
US X NZ	Games Howell	1.095	0.200	<0.001
AU x NZ	Games Howell	0.305	0.206	0.451

[a] Here we report the Levene Statistic for the CDR and SRM Variables based on the Mean.
Mean difference is calculated as mean[b] - mean[c].

2.5.6. Quantitative phase – Construction of concept maps

To enable replication, we provide an illustration of the development of the concept maps for the UK data. These require the tabulation of the retained attribute associations shown in Table 19 followed by a chi-square calculation of expected association counts for each attribute for each concept. The difference between actual and expected association counts is converted into percentages in Table 20, and then given a graphical presentation in Figure 7 below. For completeness, we present graphical presentations for the US, Australia, and NZ in Figures 8-10.

Table 19: Final attribute counts (UK data)

	BECCS	DACSS	EW	MCB	SAI	MIS	TOTAL	%
Unknown effects	252	268	324	359	407	383	1993	22%
Risky	185	183	239	263	389	323	1582	17%
Artificial	134	161	144	228	253	256	1176	13%
Eyesore	92	117	62	51	60	85	467	5%
Quick-fix	73	85	85	109	109	84	545	6%
Understandable	183	162	151	101	82	92	771	9%
Controllable	155	163	131	110	55	68	682	8%
Environmentally friendly	176	146	161	97	51	89	720	8%
Long-term sustainability	172	148	135	75	56	87	673	7%
Cost effective	107	80	105	56	45	60	453	5%
TOTAL	1529	1513	1537	1449	1507	1527	9062	
%	17%	17%	17%	16%	17%	17%		

Table 20: Percentage deviations from expected attribute counts (UK data)

	BECCS	DACSS	EW	MCB	SAI	MIS	Average (absolute values)
Unknown effects	-6%	-4%	-1%	3%	5%	3%	4%
Risky	-5%	-5%	-2%	1%	8%	4%	4%
Artificial	-4%	-2%	-4%	3%	4%	4%	3%
Eyesore	1%	3%	-1%	-2%	-1%	0%	1%
Quick-fix	-1%	0%	0%	2%	1%	-1%	1%
Understandable	3%	2%	1%	-2%	-3%	-2%	2%
Controllable	3%	3%	1%	0%	-4%	-3%	2%
Environmentally friendly	4%	2%	3%	-1%	-5%	-2%	3%
Long-term sustainability	4%	2%	1%	-2%	-4%	-2%	3%
Cost effective	2%	0%	2%	-1%	-2%	-1%	1%

Figure 7: Concept maps for the United Kingdom

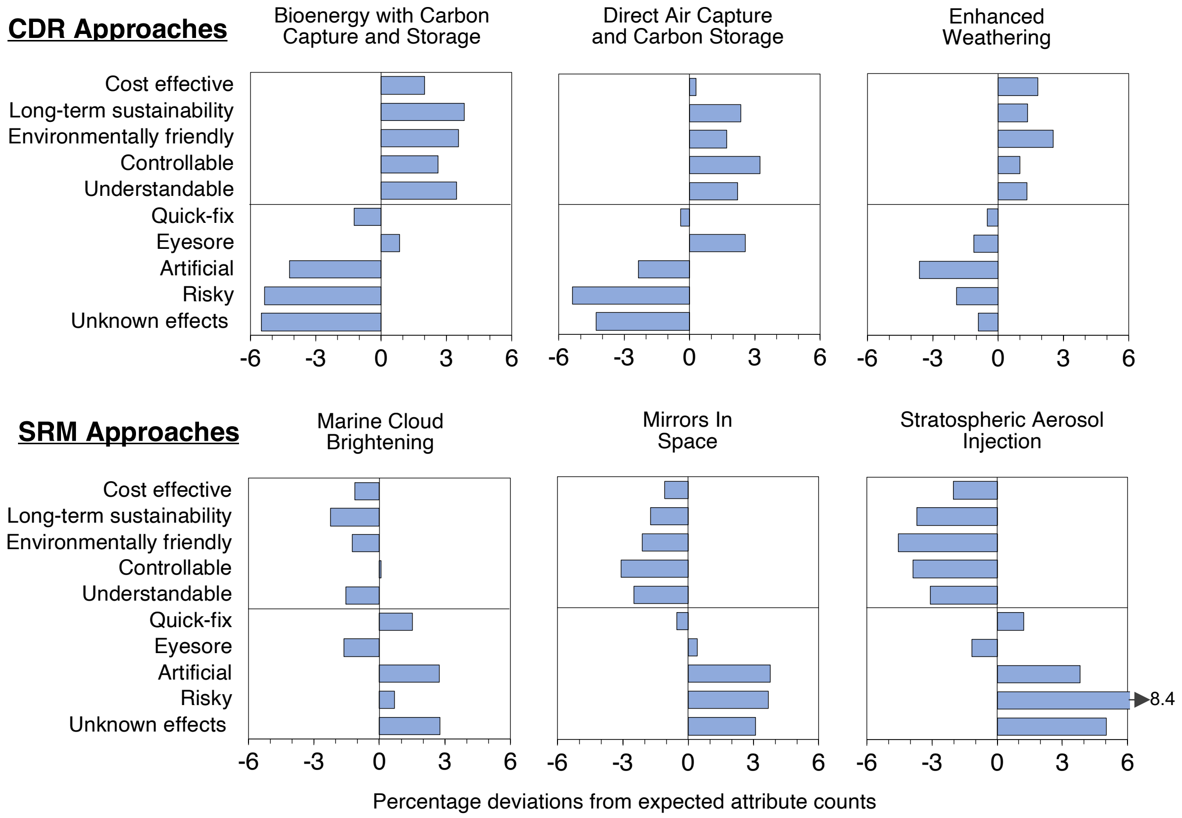


Figure 8: Concept maps for the United States

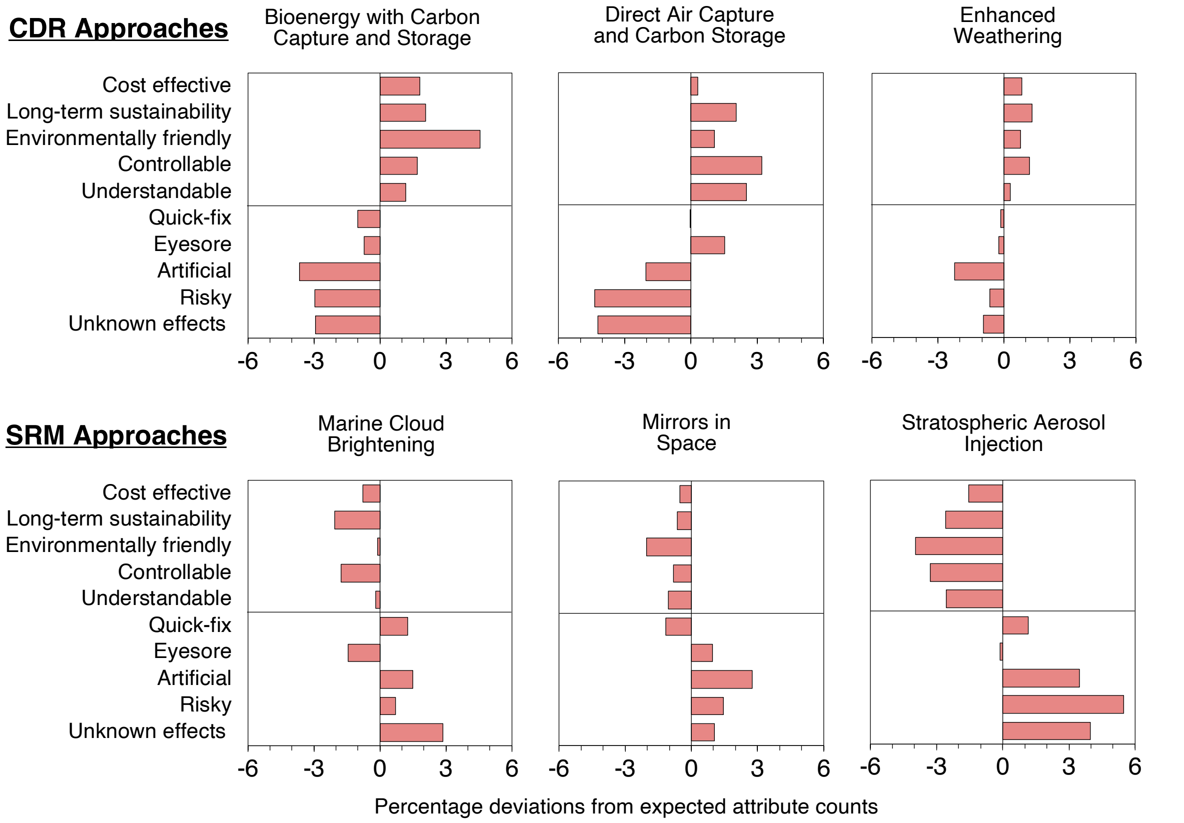


Figure 9: Concept maps for Australia

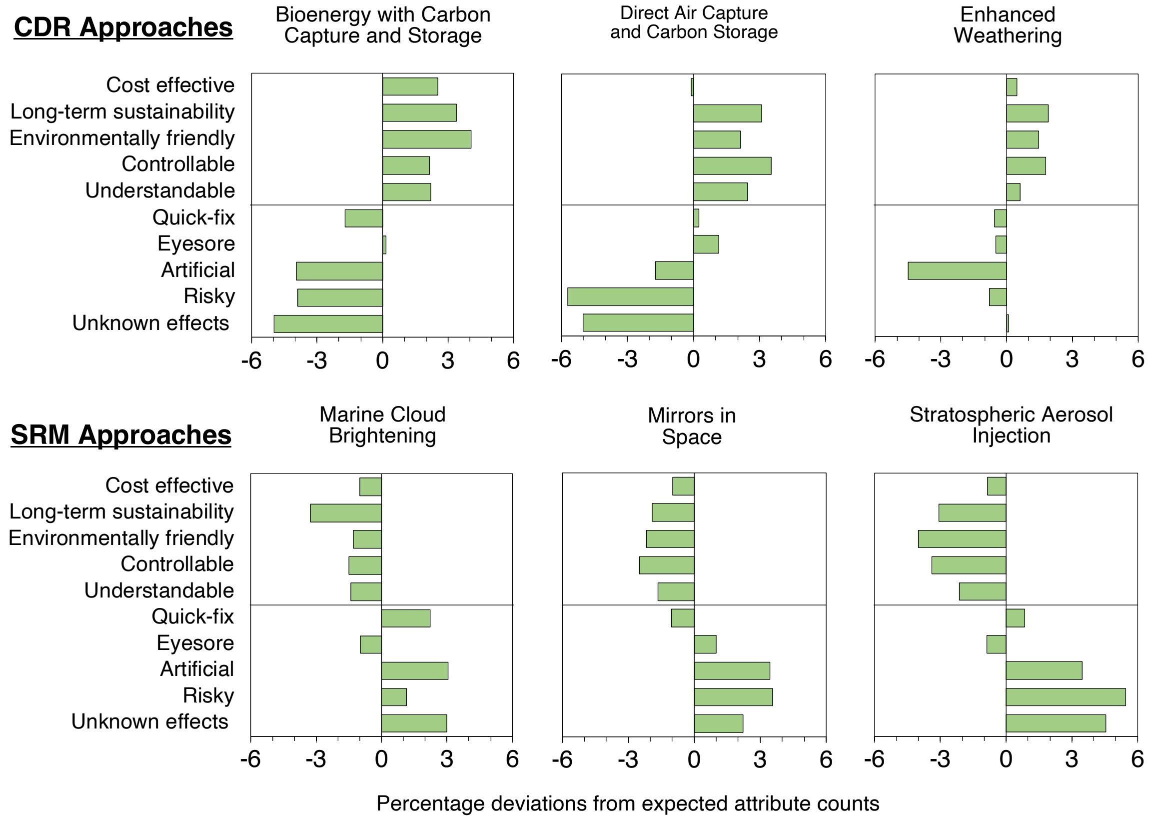
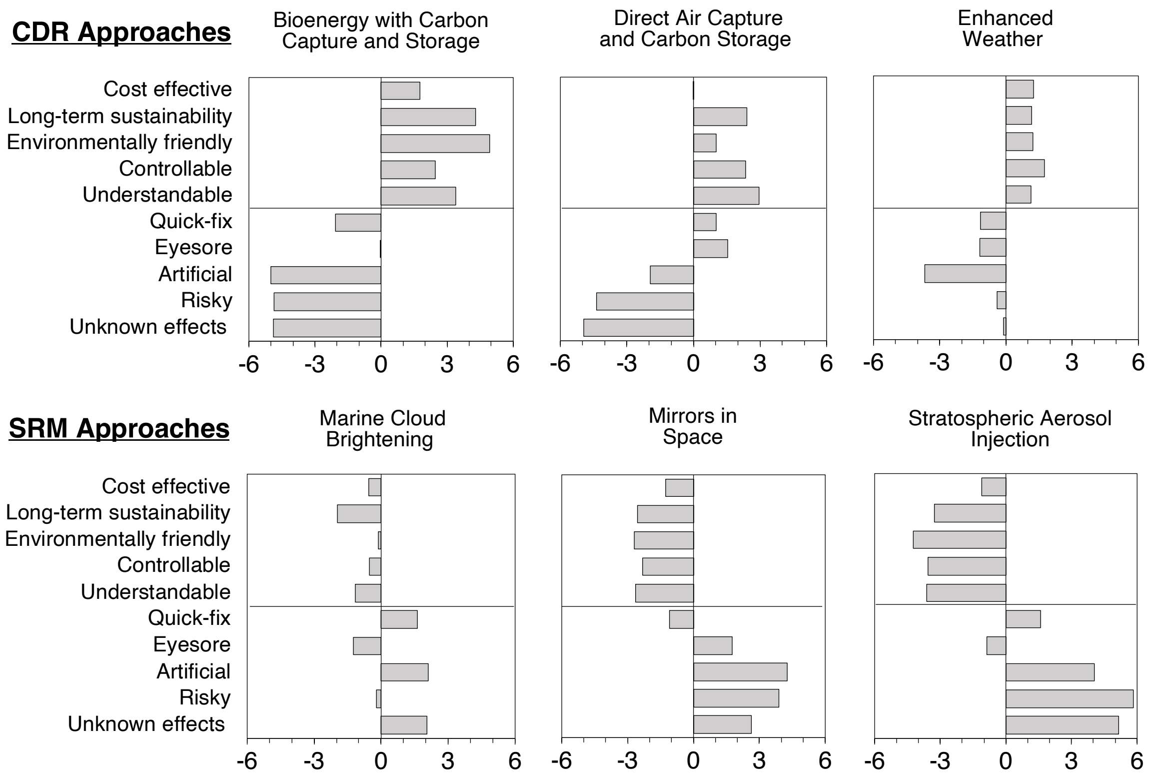


Figure 10: Concept maps for New Zealand



ARTICLE 2:
PUBLIC ENGAGEMENT WITH EMERGING TECHNOLOGIES: DOES REFLECTIVE THINKING AFFECT SURVEY RESPONSES?

Preface:

This chapter contains work already published by the authors in the peer reviewed journal *Public Understanding of Science* (Impact Factor: 2.976). The final authenticated version is available at the DOI below.

Carlisle, D. P., Feetham, P. M., Wright, M. J., & Teagle, D. A. H. (2021). Public engagement with emerging technologies: Does reflective thinking affect survey responses? *Public Understanding of Science* https://doi.org/10.1177/09636625211029438

The full article and supplementary information are reproduced in the following chapter. While the article structure and content are preserved, some minor changes are made to ensure consistency across this thesis. The reference list is also aggregated at the end of the thesis.

This project has been evaluated by peer review and judged to be low risk (4000020070)

Summary:

Aim: Establish the effect of intuitive vs. reflective thinking in survey research on public perceptions of six climate engineering technologies.

Main Research Questions:

RQ2.1 To what extent does encouraging intuitive or reflective thinking affect public perceptions of climate engineering?

RQ2.2 To what extent do public perceptions of climate engineering differ between participants who choose to consider their responses for longer than those that respond quickly?

Method: Large scale quantitative survey experiment (UK; n = 1558) including the UK data drawn from Publication One as a control. Experimental treatments instructed participants to either respond quickly or to take time to consider their responses.

Findings: Perceptions of climate engineering were remarkably consistent between experimental groups. However, participants with stronger views tended to take more time to consider their response, without prompting.

Contributions: The findings suggest that deeper participant consideration is not needed to elicit participant’s perceptions of emerging technologies. Despite criticism of the rapid responses elicited by public engagement surveys, the research concludes that self-administered surveys remain a useful tool for large-scale public engagement.

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STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Daniel Carlisle
Name/title of Primary Supervisor:	Prof. Malcolm Wright
Name of Research Output and full reference:	
Carlisle, D. P., Feetham, P. M., Wright, M. J., & Teagle, D. A. H. (2022). Public engagement with emerging technologies: Does reflective thinking affect survey responses? Public Understanding of Science, 31(5), 660-670. https://doi.org/10.1177/0963662	
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Date:	02-Jun-2022
Primary Supervisor's Signature:	Wright, Malcolm Digitally signed by Wright, Malcolm Date: 2022.06.01 14:36:57 +12'00'
Date:	1-Jun-2022

(This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis)

3.0 Public engagement with emerging technologies: Does reflective thinking affect survey responses?

Abstract: Researchers disagree on the extent that brief survey methods accurately reflect citizens' opinions of unfamiliar scientific concepts. We examine whether encouraging participants to engage in more reflective thinking affects their perceptions of emerging climate technologies. Drawing on dual process theories of reasoning, we apply experimental manipulations to encourage fast, intuitive thinking or slow, reflective thinking when responding to an online survey. Similarities in concept evaluation time between the Control and the Intuitive treatment groups indicates that citizens default to fast intuitive judgements to form opinions. However, despite a successful manipulation check, the reflective treatment group did not show any substantively different results. Therefore, encouraging additional thinking is unlikely to shift public perceptions. Post-hoc analysis suggests participants with stronger views may nonetheless take more time to consider their response, without prompting. These findings support the validity of surveys as a method for eliciting stable and meaningful public perceptions of emerging technologies.

3.1. Introduction

Self-administered questionnaires are a common tool for eliciting public opinion on a large scale. They are potentially helpful for gauging citizens' responses to unfamiliar scientific concepts, such as the emerging climate technologies 'carbon dioxide removal' (CDR) and 'solar radiation management' (SRM)[3] that some scientists believe may be necessary to avoid the worst impacts of climate change (Caldeira & Keith, 2010; MacMartin et al., 2018).

Previous research found that public awareness of CDR and SRM technologies was relatively low and perceptions broadly negative, although more so for SRM than CDR (Carlisle, Feetham, Wright, & Teagle, 2020; Cummings et al., 2017). Thus, if global warming mitigation efforts prove insufficient, and should CDR or SRM climate responses be required, emergent public concern may hinder their development and deployment. However, as most citizens will be unfamiliar with such emerging technologies, there is concern about the extent that survey respondents can give meaningful evaluations without first thoroughly reflecting on the technologies in question. What remains unclear is whether researchers can encourage survey participants to engage in more reflective information processing, and if so, whether their responses differ as a result. The current research uniquely addresses this knowledge gap by exploring the extent that encouraging slow, reflective thinking affects survey participants' evaluations of emerging technologies.

3.1.1. Dual-process theory and public engagement

Dual-process theories offer a useful framework for examining the impact of reflective thinking on citizen evaluations of emerging technologies. Developed in cognitive psychology and behavioural economics, dual process theories posit that human reasoning occurs through two distinct types of information processing, referred to as Type 1 and Type 2 processes (Evans, 2011). Most decision

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[3] Carbon dioxide removal (CDR) approaches extract and sequester carbon from the atmosphere to offset greenhouse gas emissions whereas solar radiation management (SRM) approaches reflect a portion of sunlight away from the Earth to counteract rising temperatures. Collectively these technologies are sometimes referred to as 'climate engineering'.

making relies on Type 1 processes that correlate with fast, intuitive thinking to conserve cognitive resources. Type 2 processes correlate with slower, reflective reasoning that can override initial Type 1 reactions but require substantially more cognitive effort (Evans, 2003; Evans & Stanovich, 2013; Kahneman, 2011). Accordingly, since survey respondents have limited time and motivation, they are likely to rely predominantly on Type 1 rather than Type 2 thinking.

Type 1 and Type 2 reasoning can cause individuals to arrive at different conclusions during decision making tasks (Evans & Stanovich, 2013), suggesting that encouraging survey respondents to engage in reflective thinking could affect their survey responses. For example, one study found mixed evidence that respondents who spent more time considering information about climate engineering technologies were comparatively more negative in their overall evaluations (Feetham, 2016). Other studies found that reflective thinkers[4] demonstrated lower acceptance of climate engineering technologies (Braun, Merk, et al., 2018) and, in some instances, hold more stable preferences over time (Braun, Rehdanz, et al., 2018). Notably, these studies draw their conclusions from correlations rather than establishing causation through experimental tests, and therefore, it is unclear whether reflective thinking causes more concern, or whether more concern causes greater reflection.

To advance the debate, the present research tests the extent that intuitive Type 1, and reflective Type 2 thinking influences perceptions of CDR and SRM technologies. The current study draws on a quantitative technique (Carlisle et al., 2020; Wright et al., 2014) to measure public opinion of six CDR and SRM technologies. We introduce additional experimental treatments to encourage either fast, intuitive Type 1 or slower, reflective Type 2 thinking (Evans & Stanovich, 2013; Konopka et al., 2019) to determine *whether reflective thinking affects participants' evaluations of CDR and SRM techniques*. A further post-hoc comparison considers whether evaluations change by the time taken

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[4] Reflective thinking was measured using the Cognitive Reflection Test; a tool for measuring an individuals' disposition for reflective thinking (Frederick, 2005).

to reflect on relevant portions of the survey (Feetham, 2016; Konopka et al., 2019). Consideration of results from the experimental manipulation with those of the post-hoc comparison cast light on *the direction of causation between reflective Type 2 thinking and changes in evaluations*. The research makes a novel contribution by applying dual-process theories to survey-based public engagement research and presents practical implications for researchers conducting meaningful public engagement on mitigation of global warming.

3.2. Method

Using a large quantitative survey (n = 1558) we measure public perceptions by presenting participants with information about CDR and SRM technologies and analysing the attributes (e.g. *risky* or *environmentally friendly*) that are brought to mind (Carlisle et al., 2020; Wright et al., 2014). The method draws on associative network theories of memory (Anderson & Bower, 1973) as well as techniques developed by branding experts to model mental associations with a brand or product (Romaniuk, 2013; Wright et al., 2014).

We apply split-sample experimental treatments to encourage either rapid, intuitive Type 1 thinking (n = 434) or slower, reflective Type 2 thinking (n = 373), as well as a Control treatment (n = 751). Finally, we use statistical techniques to establish whether the Type 1 or Type 2 manipulations influence participant responses to the survey. That is, whether reflective thinking affects participant evaluations of CDR and SRM techniques.

3.2.1. Materials

The questionnaire begins with a general introduction on the topic of global warming, three warmup questions, and further information on potential responses to climate change. Next, participants evaluate three CDR technologies and three SRM technologies individually. These are bioenergy with carbon capture and storage (BECCS), direct air capture and carbon storage (DACCS), enhanced weathering (EW), marine cloud brightening (MCB), mirrors in space (MIS), and stratospheric aerosol injection (SAI)[5]. Since participants are unlikely to have prior knowledge of CDR and SRM technologies we provide a visual diagram and short description for each technology in separate concept evaluation blocks (Figure 14).

The primary data is derived from the attribute selection task used to measure memory associations with the six technologies (Carlisle et al., 2020; Wright et al., 2014). Following each concept description, participants are asked to select attributes from a pre-determined list that they associate with each technology (*unknown effects, unpredictable, risky, artificial, quick-fix, eyesore, understandable, controllable, environmentally friendly, beneficial, long-term sustainability,* and *cost-effective;* see Figures 15-17). Additional Likert-style questions are used to assess respondent's understanding of the technology, support for small scale trials, and belief that each technology would help address global warming. Finally, participants answer some general questions about their prior awareness of the technologies, and demographic characteristics. To enable replication and transparency, we provide a more detailed account of the materials, methods, and measures in the supplementary information (Section 3.5).

3.2.2. Experimental manipulations

For the experimental treatments we draw on manipulations developed in previous dual process research, designed to enhance or suppress Type 2 processes via direct instruction (Evans & Stanovich, 2013). Participants in the *Control* treatment proceed through the questionnaire with no further additions or manipulations. In the *Type 1* treatment, participants are forced to rely on fast, Type 1 thinking by using time pressure to inhibit slower Type 2 thinking (Evans & Curtis-Holmes, 2005;

[5] BECCS involves the combustion of bioenergy crops to produce renewable energy. The resulting carbon emissions are captured and stored. DACCS uses artificial structures to filter and store carbon dioxide from the atmosphere. EW involves spreading finely ground minerals to accelerate a chemical reaction that draws down carbon from the atmosphere. MCB involves spraying seawater into low marine clouds to increase their albedo and reflect incoming solar radiation. MIS involves placing reflective materials in orbit to reduce incoming solar radiation. SAI involves spreading sulphate particles into the stratosphere to reflect a portion of incoming solar radiation.

Evans & Stanovich, 2013; Konopka et al., 2019). In the *Type 2* treatment, reflective thinking is encouraged by motivating and instructing respondents (Evans & Stanovich, 2013) to read each description thoroughly and to expect their knowledge to be tested. Below are examples of the instructions given to participants in the *Type 1* and *Type 2* treatments both before and during each concept evaluation (see also Figures 13, 16, and 17):

Type 1: **"***It is important to* ***make your decisions quickly****. Please do not spend much time evaluating choices before you tick the boxes."*

Type 2: *"At the end of each section you will be asked a random question about the description you have just read. You will* ***not*** *be able to go back to check, so it is important that you* ***read each description thoroughly****."*

On a new page, following each concept evaluation, participants in the *Type 2* treatment are also asked a multi-choice quiz item based on the concept they had just evaluated (Figure 18).

A further comparison of Type 1 versus Type 2 thinking is available by considering time taken to complete the task for each concept block (Feetham, 2016; Konopka et al., 2019). In this case, quicker respondents are assumed to engage predominantly in intuitive Type 1 thinking, and slower respondents to engage in relatively more reflective Type 2 thinking. Categorising respondents by time taken is found to give similar results to other manipulations of Type 1 and Type 2 thinking (Konopka et al., 2019)

3.2.3. Sample

UK participants (*n* = 1558) were recruited online using a commercial panel provider, Dynata (https://www.dynata.com), in 2018, with panel members recruited via topic-blind survey invitations until demographic quotas are met and allocated to one of three treatments; *Control*, *Type 1*, or *Type 2*. Overall, the sample characteristics show a satisfactory spread of demographics with an even gender split (50% male and female) and a mean age of 52 (SD = 17). Table 25 outlines the full demographic breakdown.

3.3. Results

3.3.1. Type 1 and Type 2 manipulations

The success of the primary experimental manipulations is measured using timers for the duration of the participant interaction with the concept evaluation block. Comparisons of the concept evaluation times (Table 21) indicate the manipulations successfully encouraged participants in the slow Type 2 treatment to reflect on the information for approximately two minutes longer than the Type 1 treatment (based on the 5% trimmed mean). Statistical tests ($\chi^2(2) = 47.887$, $p < 0.001$) confirm participants in the Type 2 treatment group take significantly longer than participants in the Type 1 treatment ($p < 0.001$) and the Control treatment ($p < 0.001$). However, there was no significant differences in time-taken between the Type 1 and Control treatments ($p = 0.305$).

Table 21: Concept evaluation time by treatment

Treatment	Mean	Standard Deviation	Mean (5% Trimmed)
Type 1	4 min 53 s	3 min 50 s	4 min 28 s
Control	6 min 00 s	12 min 17 s	4 min 52 s
Type 2	7 min 17 s	8 min 6 s	6 min 26 s

A likely explanation for the non-significant differences between the Type 1 and Control is that participants in the Control treatment automatically default to fast Type 1 thinking and therefore take a similar amount of time to evaluate concepts as the Type 1 treatment. This conclusion aligns with dual processing theories that suggest Type 1 processes are the default form of human reasoning (Evans, 2007; Evans & Stanovich, 2013; Kahneman & Frederick, 2002) and with more general observations that survey mechanisms by default tend to elicit fast-intuitive, rather than slow-reflective responses (Wright et al., 2014). Thus, it is not surprising there are no substantial differences in concept evaluation time between the Type 1 and Control treatments.

3.3.2. Awareness and understanding

Few participants (19%) report prior knowledge of the CDR and SRM proposals across the three treatment groups (see also, Carlisle et al., 2020; Cummings et al., 2017) indicating most rely on the information provided to inform their evaluations. To check the adequacy and understanding of these concept materials we ask whether participants believe they can explain each concept to somebody else. Responses are acceptable with 44% of participants across the three treatments agreeing (ranging from 38% - 48% between technologies), 37% neutral, and only 19% disagreeing. Further analysis (see supplementary materials) indicates no significant differences in mean understanding scores between treatments ($F_{(.05, 2, 1555)} = 0.95$, $p = 0.39$).

3.3.3. Attribute popularity (salience)

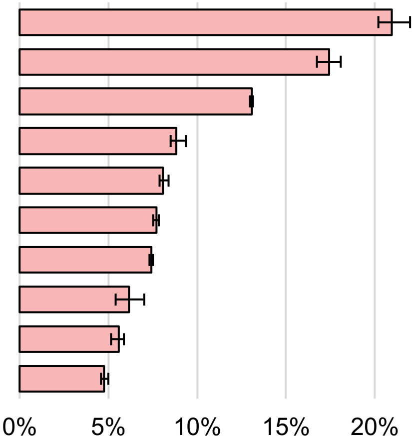
To assess whether *reflective Type 2 thinking changes participant evaluations of CDR and SRM techniques* we compare differences in attribute popularity (salience) between treatments. Attribute salience is measured as each attributes' percentage share of the total associations (Table 22). In line with previous research (Carlisle et al., 2020; Wright et al., 2014) the negative attributes *unknown effects, risky,* and *artificial* rank the highest by popularity and account for over 50% of the total attribute associations.

The percentage shares of associations show little variation between treatments with no more than one percentage point deviation from the overall mean (see error bars, Table 22) and correlations between treatments of no less than $r = 0.99$. Likewise, when the data is split by CDR and SRM technologies, the treatments retain minimal variation with correlations of no less than $r = 0.96$ (see Table 30 and Table 31). Thus, there is no evidence to suggest that reflective Type 2 thinking affects the salience or retrieval of certain attributes in memory.

Table 22: Attribute popularity (salience) for CDR and SRM approaches, as % of associations

Rank	Attribute	Type 1	Control	Type 2
1	Unknown effects	21	22	20
2	Risky	17	17	18
3	Artificial	13	13	13
4	Understandable	9	9	9
5	Environmentally friendly	8	8	8
6	Controllable	8	8	8
7	Long-term sustainability	7	7	8
8	Quick-fix	7	6	5
9	Eyesore	6	5	6
10	Cost effective	5	5	5

Mean
(Error bars show range between treatments)



Attribute associations are also aggregated to give an overall count of associations per technology and mean count of associations per respondent (Table 23). The data indicate respondents associate approximately two attributes with each technology (mean ranging from 1.9 – 2.2). Aggregating the mean association metric reveals participants in the Type 1 treatment retrieved slightly more attributes, however both ANOVA ($F_{(.05,\ 2,\ 1555)} = 1.35$, $p = 0.26$) and a Kruskal-Wallis test ($\chi^2(2) = 1.07$, $p = 0.59$) indicate the differences are non-significant. Thus, there is no evidence to suggest reflective thinking causes respondents to retrieve more information (attribute associations) from memory.

3.3.4. Concept evaluations

To compare participants positive (or negative) perceptions of CDR and SRM technologies we calculate a 'net positive' metric as the percentage count of positive associations for each technology less the percentage count of negative associations, presented numerically in Table 23 and graphically in Figure 11.

Table 23: Memory associations for CDR and SRM approaches as counts and % net positive associations

	Bioenergy with Carbon Capture and Storage	Direct Air Capture and Carbon Storage	Enhanced Weathering	Marine Cloud Brightening	Mirrors in Space	Stratospheric Aerosol Injection	Total
Count of Associations							
Type 1 (*n* = 434)	953	916	884	892	916	933	5494
Control (*n* = 751)	1529	1513	1537	1449	1527	1507	9062
Type 2 (*n* = 373)	755	764	709	743	769	788	4528
Mean associations per respondent							
Type 1 (*n* = 434)	2.2	2.1	2.0	2.1	2.1	2.1	12.7
Control (*n* = 751)	2.0	2.0	2.0	1.9	2.0	2.0	12.1
Type 2 (*n* = 373)	2.0	2.0	1.9	2.0	2.1	2.1	12.1
Net positive associations							
Type 1 (*n* = 434)	7%	-5%	-15%	-42%	-51%	-55%	-27%
Control (*n* = 751)	4%	-8%	-11%	-39%	-48%	-62%	-27%
Type 2 (*n* = 373)	3%	6%	-18%	-35%	-46%	-62%	-25%

The net positive metric yields similar findings to previous studies (Carlisle et al., 2020; Wright et al., 2014) with the three SRM techniques perceived more negatively than the three CDR approaches. Stratospheric aerosol injection remains the most negatively perceived approach in all three treatments with negative attributes accounting for over three quarters of the total attribute associations. Bioenergy with carbon capture and storage remains the most positively perceived approach for the Control and Type 1 treatments with positive attribute associations accounting for over half of the total associations. However, in the Type 2 treatment direct air capture surpasses BECCS as the most positively perceived approach, though the other four technologies retain the same rank order.

To establish whether the minor differences between groups are significant, we conduct ANOVA for the CDR and SRM net positive associations variables between treatments. ANOVA reveals the differences in net positive associations between treatments are non-significant for both CDR ($F_{(.05, 2, 1555)} = 0.19$, $p = 0.83$) and SRM ($F_{(.05, 2, 1555)} = 0.32$, $p = 0.73$). Thus, we find no evidence to suggest Type 2 thinking affects participants' positive (or negative) perceptions of CDR and SRM technologies.

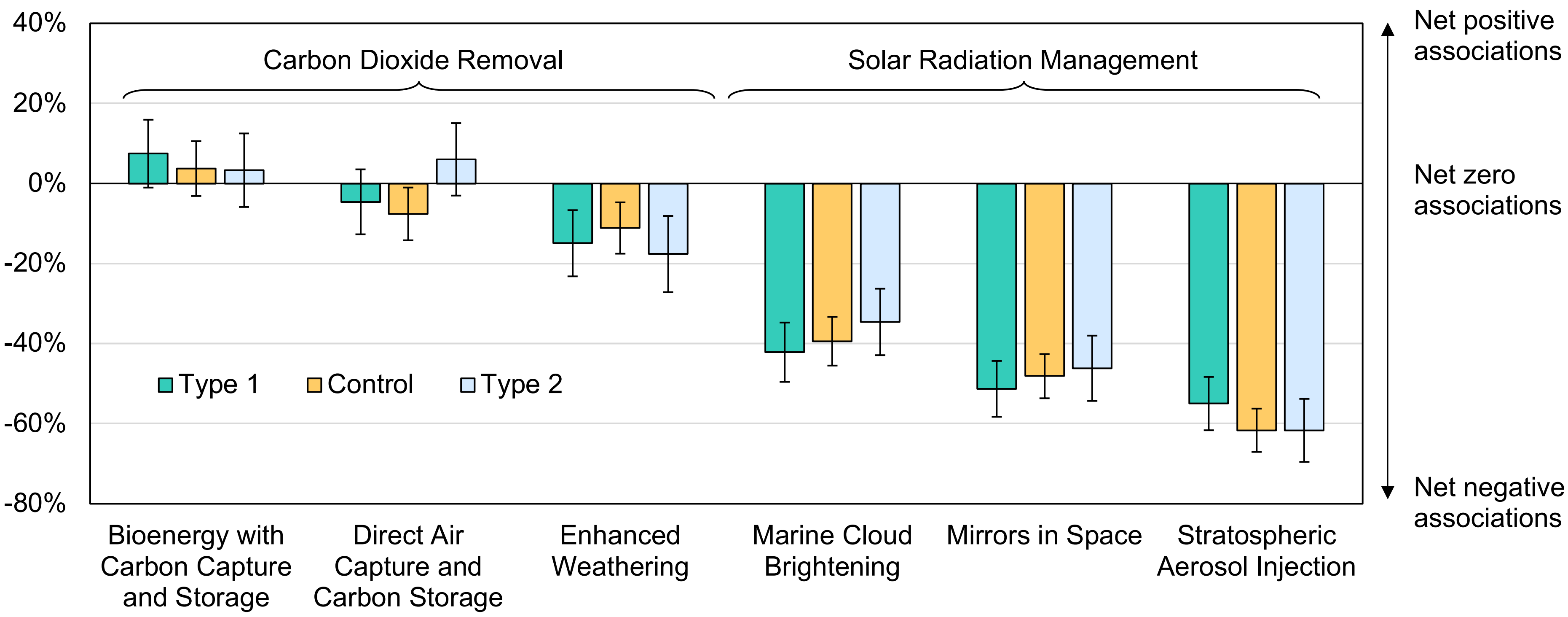


Figure 11: Net memory associations for climate technologies. *Public perceptions of SRM remain more negative than CDR and are relatively unaffected by Type 1 and Type 2 manipulations. Error bars show 95% Confidence Intervals.*

3.3.5. Response time

Within each treatment, participants differ substantially in their concept evaluation time, suggesting reflective thinking could vary by participant. Since Type 1 thinking correlates with fast, automatic responding and Type 2 thinking correlates with slow, reflective responding (Evans & Stanovich, 2013) we follow Feetham (2016) and Konopka et al. (2019) in treating time taken for concept evaluation as a proxy for reflection – that is, as a further post-hoc comparison of Type 1 and Type 2 thinking.

Scatter plots reveal heteroscedasticity and some extreme values for the concept evaluation time variable. Accordingly, we exclude sixteen outliers across the three treatments using Mahalanobis distance and use Kendall Tau-b non-parametric correlations to compare concept evaluation times (Table 24). As a further robustness check, we replicate the correlational analysis using three further samples from the United States (n = 746), Australia (n = 763), and New Zealand (n = 729) collected at the same time with the same questionnaire format as the UK Control treatment.

Across the three UK treatments and three additional countries, there are significant but small ($r < 0.30$) negative correlations between concept evaluation time and SRM net positive associations. These results indicate that participants who spent more time considering the information were also more negative toward SRM. Smaller negative correlations are also detected between concept evaluation time and the CDR net positive variable in the United States, Australia, and New Zealand. This provides some evidence that reflective Type 2 thinking is associated with stronger (in this case more negative) views. However, as this evidence was only found in the post-hoc comparison, and not the experimental manipulations, the results suggest that those with strong views are somewhat likely to engage in more reflective thinking, rather than reflective thinking causing stronger views.

Table 24: Correlations with net positive and concept evaluation time variables

	Test Statistic	Test Statistic Value	P value	Bonferroni-corrected critical P value
Type 1 (UK) Treatment				
Carbon Dioxide Removal	$\mathbf{r}_{\tau(431)}$	-0.055	0.099	0.025
Solar Radiation Management	$\mathbf{r}_{\tau(431)}$	-0.249	0.000	0.025
Control (UK) Treatment				
Carbon Dioxide Removal	$\mathbf{r}_{\tau(745)}$	-0.057	0.025	0.025
Solar Radiation Management	$\mathbf{r}_{\tau(745)}$	-0.291	0.000	0.025
Type 2 (UK) Treatment				
Carbon Dioxide Removal	$\mathbf{r}_{\tau(370)}$	-0.073	0.042	0.025
Solar Radiation Management	$\mathbf{r}_{\tau(370)}$	-0.281	0.000	0.025
US Sample				
Carbon Dioxide Removal	$\mathbf{r}_{\tau(732)}$	-0.090	0.000	0.025
Solar Radiation Management	$\mathbf{r}_{\tau(732)}$	-0.279	0.000	0.025
AU Sample				
Carbon Dioxide Removal	$\mathbf{r}_{\tau(762)}$	-0.096	0.000	0.025
Solar Radiation Management	$\mathbf{r}_{\tau(762)}$	-0.264	0.000	0.025
NZ Sample				
Carbon Dioxide Removal	$\mathbf{r}_{\tau(708)}$	-0.068	0.008	0.025
Solar Radiation Management	$\mathbf{r}_{\tau(708)}$	-0.188	0.000	0.025

3.4. Discussion

Some researchers have voiced concerns that quantitative surveys may not accurately reflect public perceptions of unfamiliar technologies as participants have only a short period to form an opinion on limited information (Merk et al., 2019). Contrary to this concern, our research indicates that participants are not forced to engage in fast, limited information processing, but rather, they choose to. Our study finds no significant difference in concept evaluation times between the Type 1 treatment (who were encouraged not to spend long thinking about their response) and the Control treatment (who received no specific instructions). Conversely the Type 2 treatment (who were encouraged to read each description thoroughly and told they would be tested on their knowledge) took significantly longer in the concept evaluation task. The non-significant differences between the Type 1 and Control treatments suggest that most citizens rely on fast intuitive thinking by default to evaluate emerging climate technologies, rather than slow, reflective thinking. Thus, eliciting fast, intuitive responses with traditional survey methods may not threaten external validity after all. Rather, survey responses may use the same fast, intuitive information processing that the broader public rely on to form opinions on emerging technologies.

Additionally, we find little evidence to suggest that encouraging reflective thinking impacts public perceptions of CDR and SRM techniques. Though the experimental manipulation successfully encouraged participants to spend more time reflecting on the information provided, our statistical analyses found no significant effect on participants' perceptions of CDR or SRM. Conversely, respondents who show higher concern toward emerging technologies may engage in more reflective thinking without prompting. Accordingly, our findings suggest there is little for public engagement researchers to gain from actively encouraging reflective thinking during survey research.

In line with dual-process theories (Evans, 2007; Evans & Stanovich, 2013; Kahneman & Frederick, 2002) and the low-information rationality model (Popkin, 1994; Scheufele, 2006) these findings suggest that public perception of CDR and SRM is dominated by fast intuitive thinking, rather than slower, reflective reasoning. Accordingly, the public are unlikely to devote substantial time and cognitive effort toward processing detailed information from science communicators. Instead, communications should focus more on salient aspects (e.g., unknown effects, risk, and artificiality for CDR and SRM) that contribute the most to overall public perceptions of emerging climate technologies.

Meanwhile, with the rapid rise in global mean temperature, social scientists urgently need to expand global public engagement efforts and identify the most acceptable pathways for addressing climate change. The current study suggests that, despite concerns about external validity, large scale quantitative methods remain useful tools for consulting citizens worldwide on emerging climate technologies. With the continued worldwide inaction on global emissions, researchers must move quickly to provide a representative voice for the global public and ensure citizens' concerns are heard. One effective way of doing so is to use the techniques developed from memory association theory to systematically measure public perceptions through online surveys.

3.4.1. Limitations and future directions

The findings above apply to public engagement research within the context of self-administered surveys. Future research could investigate whether reflective thinking has a similarly negligible impact on public perceptions during deliberative methods of public engagement that purportedly elicit more considered responses compared to traditional survey methods (Macnaghten & Szerszynski, 2013).

3.5. Supplementary information

This supplementary information provides details that are omitted from the main manuscript and is divided into nine sections:

- Survey Materials
- Sample Demographics
- Measures
- Kendall Tau-b nonparametric correlations test for overlapping mental constructs
- Net positive variable statistics
- Univariate Tests
- Multivariate Tests
- Attribute Popularity (Salience) Split by CDR and SRM

3.5.1. Survey materials

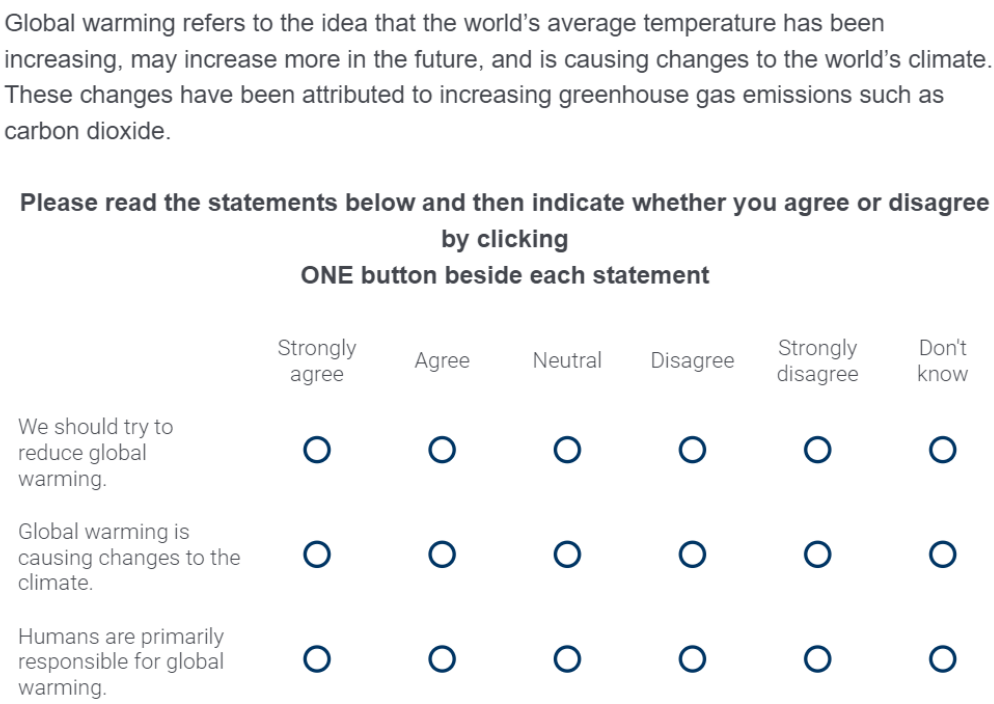
Prior to beginning the survey, participants read an information sheet and indicate their consent by proceeding. The questionnaire begins with the survey introduction and warmup questions (Figure 12), followed by the concept introductions, including instructions specific to each experimental treatment (Figure 13).

Next, participants evaluate each of the three CDR technologies and three SRM technologies individually, in a randomised order. Since participants are unlikely to have prior knowledge of CDR and SRM technologies we provide a visual diagram and short description for each technology (Figure 14). The concept imagery and descriptions are carefully designed using matching criteria for colour, scale, content, and length (93-100 words). Based on the concept materials for each technology, participants are asked to select attributes from a list, using a free choice, pick any format (Romaniuk, 2013) that they associate with each technology (Figure 15). The list contains attributes generated in previous studies (Carlisle et al., 2020; Wright et al., 2014) using qualitative depth interviews in 2012 (n = 30) and 2018 (n = 15) that citizens associate with, or use to differentiate between, the six technologies. The presentation order of concepts and attributes are randomised to reduce order effects. Participants receive additional instructions in the Type 1 (Figure 16) and Type 2 (Figure 17) experimental treatments. The concept evaluation block also includes three further items to measure perceived technological feasibility, support for small scale trials, and participant understanding.

Following each concept evaluation block, participants in the Type 2 treatment are also asked a brief, multichoice quiz question about each of the concept descriptions they read (Figure 18). The presentation order of the possible quiz answers is randomised, and participants are unable to return to the previous page to check their answer.

The survey concludes with items to measure prior awareness ("Did you know about any of these proposals before you began this survey?" – Yes/No), ecological views, and sample demographics (Table 25).

Figure 12: Survey introduction and warmup questions



Global warming refers to the idea that the world's average temperature has been increasing, may increase more in the future, and is causing changes to the world's climate. These changes have been attributed to increasing greenhouse gas emissions such as carbon dioxide.

Please read the statements below and then indicate whether you agree or disagree by clicking ONE button beside each statement

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Don't know
We should try to reduce global warming.	○	○	○	○	○	○
Global warming is causing changes to the climate.	○	○	○	○	○	○
Humans are primarily responsible for global warming.	○	○	○	○	○	○

Figure 13: Concept introductions

Control treatment

In response to global warming, 196 countries adopted the 2015 Paris Agreement under the United Nations Framework Convention on Climate Change. The aim of the agreement is to limit the global increase in temperatures to below 2° Celsius.

Alongside ways for adapting to global warming, governments and scientists are considering a range of possible solutions for achieving the 2°C goal. Some proposals include reducing global emissions, removing carbon dioxide from the air, or reflecting sunlight back into space.

We would like to know what you think about some of these proposals for removing carbon dioxide and reflecting sunlight. In the following pages we will present six proposals and ask some questions about each one. Please read the description and tick the boxes that you think apply. There are no right or wrong answers in this survey. Rather we are interested in your opinion.

→

Type 1 treatment

In response to global warming, 196 countries adopted the 2015 Paris Agreement under the United Nations Framework Convention on Climate Change. The aim of the agreement is to limit the global increase in temperatures to below 2° Celsius.

Alongside ways for adapting to global warming, governments and scientists are considering a range of possible solutions for achieving the 2°C goal. Some proposals include reducing global emissions, removing carbon dioxide from the air, or reflecting sunlight back into space.

We would like to know what you think about some of these proposals for removing carbon dioxide and reflecting sunlight. In the following pages we will present six proposals and ask some questions about each one. Please read the description and tick the boxes that you think apply. There are no right or wrong answers in this survey. Rather we are interested in your opinion.

*It is important to **make your decisions quickly.** Please do not spend much time evaluating choices before you tick the boxes.*

→

Type 2 treatment

In response to global warming, 196 countries adopted the 2015 Paris Agreement under the United Nations Framework Convention on Climate Change. The aim of the agreement is to limit the global increase in temperatures to below 2° Celsius.

Alongside strategies for adapting to global warming, governments and scientists are considering a range of possible solutions for achieving the 2°C goal. Some proposals include reducing global emissions, removing carbon dioxide from the air, or reflecting sunlight back into space.

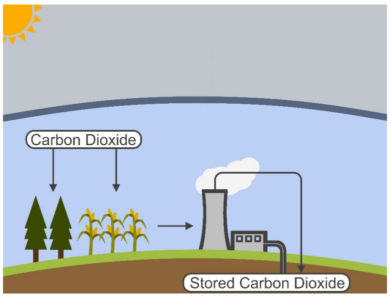
We would like to know what you think about some of these proposals for removing carbon dioxide and reflecting sunlight. In the following pages we will present six proposals and ask some questions about each one. Please read the description and tick the boxes that you think apply. There are no right or wrong answers in this survey. Rather we are interested in your opinion.

*At the end of each section you will be asked a random question about the description you have just read. You will **not** be able to go back to check, so it is important that you **read each description thoroughly.***

→

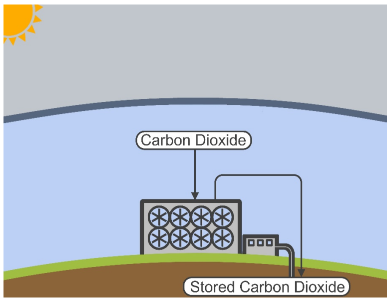
Figure 14: Concept boards

Bio-Energy with Carbon Capture and Storage (BECCS)



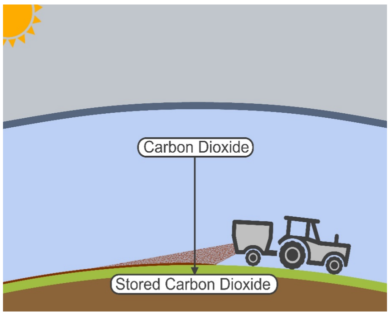
Bio-energy with Carbon Capture and Storage (BECCS) involves growing plants or 'biomass' to remove carbon dioxide from the air. The biomass is combusted to produce renewable energy. The emitted carbon dioxide is captured and stored indefinitely in underground reservoirs. Producing biomass, building infrastructure, and transporting carbon incur costs. The land requirements for BECCS could affect food production, biodiversity, water allocation, and deforestation. Producing and transporting biomass require renewable energy sources to ensure that more carbon dioxide is stored than emitted. BECCS could be introduced gradually, however, large-scale implementation and infrastructure is required to reduce global temperatures.

Direct Air Capture and Carbon Storage (DACCS)



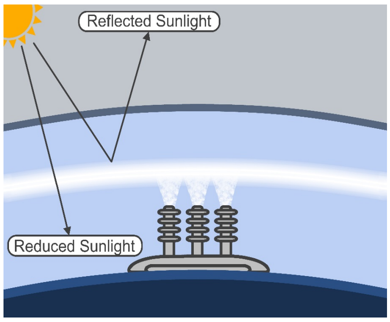
Direct Air Capture and Carbon Storage (DACCS) involves building structures that filter carbon dioxide from the air. Carbon dioxide is captured, transported, and stored indefinitely in underground reservoirs. Structures can be located anywhere and would target areas with suitable underground reservoirs. Building and operating air capture structures requires land and incurs costs. Powering the air capture structures and transporting carbon dioxide requires renewable energy sources to ensure that more carbon is stored than emitted. Direct Air Capture could be introduced gradually, however, large-scale implementation and infrastructure are required to reduce global temperatures.

Enhanced Weathering



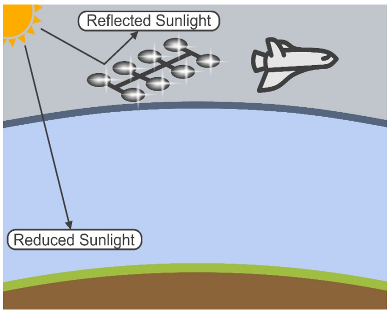
Certain rocks react with atmospheric carbon dioxide to break down or 'weather'. This reaction forms new minerals that store carbon indefinitely. Crushing and spreading the rocks accelerates carbon dioxide removal, improves soil quality, may reduce mine wastes, and could reduce ocean acidification if washed out to sea. Enhanced Weathering requires land and could affect biodiversity, human health, and leach heavy metals into soils. Mining, transporting, and spreading rocks incur costs and require renewable energy sources to ensure that more carbon is stored than emitted. Enhanced Weathering could be introduced gradually, however, large-scale implementation is required to reduce global temperatures.

Marine Cloud Brightening



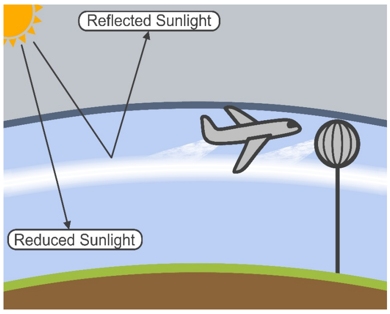
Marine Cloud Brightening involves automated ships spraying small seawater droplets above the ocean in targeted areas. Vapour forms around these droplets, increasing the number and brightness of clouds reflecting some sunlight back into space. Developing and building fleets of spraying vessels incurs costs. Cloud brightening is restricted to marine areas and may alter local rainfall patterns. Changes in light, ocean temperature, and currents may affect marine nutrient growth. Large-scale implementation and continuous applications are required to maintain the cooling effect. Temperatures would quickly revert to pre-application levels if stopped. Implementation may require international agreements.

Mirrors in Space



Mirrors in Space involves positioning reflective structures to orbit the Earth. These structures intercept and reflect some sunlight back into space, rapidly cooling the Earth. Space-craft would be used to position the materials. Space transportation incurs costs and would require large-scale investment, research, and development. Implementation would increase the number of orbital objects and could produce an uneven cooling effect, alter rainfall patterns, and change the appearance of the night sky. Large-scale implementation is required and temperatures would revert to pre-application levels if the structures were removed. Implementation would take decades and may require international agreements.

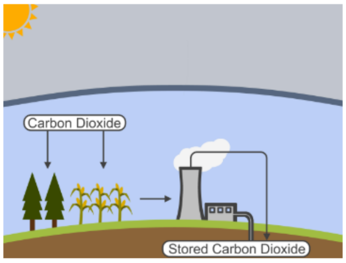
Stratospheric Aerosol Injection



Stratospheric Aerosol Injection involves spreading tiny reflective particles into the stratosphere. The particles reflect some sunlight back into space, rapidly cooling the whole Earth. Sulphate aerosols could be spread using aeroplanes or large balloons tethered to lightweight pipes. Building fleets of aeroplanes or balloons incurs costs. Stratospheric aerosols would make the sky whiter and could affect the ozone layer, rainfall patterns and crop yields. Environmental and local impacts are poorly understood. Large-scale implementation and continuous applications are required to maintain the cooling effect. Temperatures would quickly revert to pre-application levels if stopped. Implementation may require international agreements.

Figure 15: Concept evaluation block – Control treatment

Bio-Energy with Carbon Capture and Storage (BECCS)



Bio-energy with Carbon Capture and Storage (BECCS) involves growing plants or 'biomass' to remove carbon dioxide from the air. The biomass is combusted to produce renewable energy. The emitted carbon dioxide is captured and stored indefinitely in underground reservoirs. Producing biomass, building infrastructure, and transporting carbon incur costs. The land requirements for BECCS could affect food production, biodiversity, water allocation, and deforestation. Producing and transporting biomass require renewable energy sources to ensure that more carbon dioxide is stored than emitted. BECCS could be introduced gradually, however, large-scale implementation and infrastructure is required to reduce global temperatures.

Which of the descriptors in the list below do you think applies to BECCS? Please select as many as apply.

Environmentally Friendly	Controllable
Unknown Effects	Beneficial
Eyesore	Quick-Fix
Understandable	Risky
Artificial	Long-Term Sustainability
Cost Effective	Unpredictable

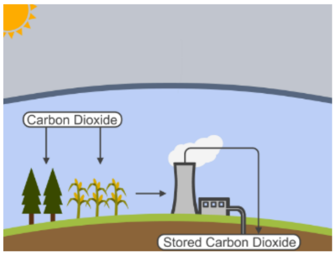
Please read the statements below and indicate whether you agree or disagree by clicking ONE button beside each statement.

	Strongly agree	Agree	Neutral	Disagree	Strongly Disagree
I would support small-scale trials of **Bio-energy with Carbon Capture and Storage** .	○	○	○	○	○
After reading the description I think that I could explain **Bio-energy with Carbon Capture and Storage** to somebody else.	○	○	○	○	○
I think **Bio-energy with Carbon Capture and Storage** would help reduce global warming.	○	○	○	○	○

→

Figure 16: Concept evaluation block – Type 1 treatment

Bio-Energy with Carbon Capture and Storage (BECCS)



Bio-energy with Carbon Capture and Storage (BECCS) involves growing plants or 'biomass' to remove carbon dioxide from the air. The biomass is combusted to produce renewable energy. The emitted carbon dioxide is captured and stored indefinitely in underground reservoirs. Producing biomass, building infrastructure, and transporting carbon incur costs. The land requirements for BECCS could affect food production, biodiversity, water allocation, and deforestation. Producing and transporting biomass require renewable energy sources to ensure that more carbon dioxide is stored than emitted. BECCS could be introduced gradually, however, large-scale implementation and infrastructure is required to reduce global temperatures.

Once again I would like to remind you to ***make your decisions quickly.***

Which of the descriptors in the list below do you think applies to BECCS? Please select as many as apply.

Beneficial	Long-Term Sustainability
Unknown Effects	Controllable
Risky	Eyesore
Artificial	Cost Effective
Environmentally Friendly	Understandable
Quick-Fix	Unpredictable

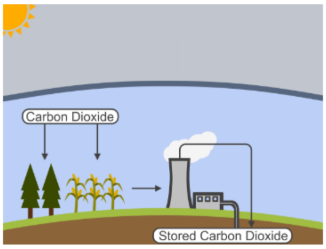
Please read the statements below and indicate whether you agree or disagree by clicking ONE button beside each statement.

	Strongly agree	Agree	Neutral	Disagree	Strongly Disagree
I think **Bio-energy with Carbon Capture and Storage** would help reduce global warming.	○	○	○	○	○
I would support small-scale trials of **Bio-energy with Carbon Capture and Storage** .	○	○	○	○	○
After reading the description I think that I could explain **Bio-energy with Carbon Capture and Storage** to somebody else.	○	○	○	○	○

→

Figure 17: Concept evaluation block – Type 2 treatment

Bio-Energy with Carbon Capture and Storage (BECCS)



Bio-energy with Carbon Capture and Storage (BECCS) involves growing plants or 'biomass' to remove carbon dioxide from the air. The biomass is combusted to produce renewable energy. The emitted carbon dioxide is captured and stored indefinitely in underground reservoirs. Producing biomass, building infrastructure, and transporting carbon incur costs. The land requirements for BECCS could affect food production, biodiversity, water allocation, and deforestation. Producing and transporting biomass require renewable energy sources to ensure that more carbon dioxide is stored than emitted. BECCS could be introduced gradually, however, large-scale implementation and infrastructure is required to reduce global temperatures.

*Once again, I would like to remind you to **read the description thoroughly**. You will be asked a random question about this description later in this survey and you will **not** be able to return to this page.*

Which of the descriptors in the list below do you think applies to BECCS? Please select as many as apply.

Understandable	Environmentally Friendly
Risky	Unknown Effects
Cost Effective	Long-Term Sustainability
Beneficial	Unpredictable
Controllable	Eyesore
Artificial	Quick-Fix

Please read the statements below and indicate whether you agree or disagree by clicking ONE button beside each statement.

	Strongly agree	Agree	Neutral	Disagree	Strongly Disagree
I think **Bio-energy with Carbon Capture and Storage** would help reduce global warming.	O	O	O	O	O
After reading the description I think that I could explain **Bio-energy with Carbon Capture and Storage** to somebody else.	O	O	O	O	O
I would support small-scale trials of **Bio-energy with Carbon Capture and Storage** .	O	O	O	O	O

→

Figure 18: Quiz questions – Type 2 treatment

Bio-energy with carbon capture and storage

On the previous page, you read a description of **Bio-Energy with Carbon Capture and Storage**.

According to the description, what happens to the Biomass once it is grown?

Please select the most correct answer.

- The biomass is buried to store the carbon underground.
- The biomass is combusted to produce renewable energy.
- The biomass is fermented to produce biofuel.

→

Mirrors in space

On the previous page, you read a description of **Mirrors in Space**.

According to the description, what would implementation involve?

Please select the most correct answer.

- Implementation could be achieved quickly but may require international agreements.
- Implementation would take decades and may require international agreements.
- Implementation would be inexpensive and would not require international agreements.

→

Marine cloud brightening

On the previous page, you read a description of **Marine Cloud Brightening**.

According to the description, what does Marine Cloud Brightening involve?

Please select the most correct answer.

- Marine Cloud Brightening involves naval ships spraying large seawater droplets into the stratosphere.
- Marine Cloud Brightening involves long hoses spraying small seawater droplets above the land in coastal areas.
- Marine Cloud Brightening involves automated ships spraying small seawater droplets above the ocean in targeted areas.

→

Enhanced weathering

On the previous page, you read a description of **Enhanced Weathering**.

According to the description, how would Enhanced Weathering be implemented?

Please select the most correct answer.

- Enhanced Weathering could be introduced internationally, and large-scale implementation would rapidly reduce global temperatures
- Enhanced Weathering could be introduced rapidly, and small-scale implementation would reduce global temperatures.
- Enhanced Weathering could be introduced gradually, however, large-scale implementation is required to reduce global temperatures.

→

Direct air capture and carbon storage

On the previous page, you read a description of **Direct Air Capture and Carbon Storage**.

According to the description, where could the air capture structures be located?

Please select the most correct answer.

- Structures can be located anywhere and would target areas with high carbon dioxide levels.
- Structures can be located in specific areas away from towns or cities.
- Structures can be located anywhere and would target areas with suitable underground reservoirs.

→

Stratospheric aerosol injection

On the previous page, you read a description of **Stratospheric Aerosol Injection.**

According to the description, what would implementation involve involve?

Please select the most correct answer.

- Large-scale implementation and a one-off application is required to maintain the cooling effect. Temperatures would eventually revert to pre-application levels if stopped.
- Large-scale implementation and continuous applications are required to maintain the cooling effect. Temperatures would quickly revert to pre-application levels if stopped.
- Large-scale implementation and continuous applications are required to achieve the cooling effect. Temperatures would remain constant if applications were stopped.

→

3.5.2. Sample demographics

Table 25: Sample demographics

	Type 1 Group (n=434)	Control Group (n=751)	Type 2 Group (n=373)	UK Census[1,2]
Age (Years)*	%	%	%	%
18 - 24	4	3	6	13
25 - 34	14	16	13	18
35 - 44	17	19	19	19
45 - 54	18	17	17	19
55 - 64	19	18	17	16
65 - 74	16	15	17	12
75 - 80	14	13	12	5
Gender				
Male	50	50	49	49
Female	50	50	51	51
	Type 1 Group (n=434)	**Control Group (n=751)**	**Type 2 Group (n=373)**	**Office for National Statistics (2018)[3]**
Household Annual Income				
Less than £12,999	3	5	5	6
£13,000-£18,999	11	11	10	11
£19,000-£25,999	15	9	11	16
£26,000-£31,999	17	14	12	13
£32,000-£47,999	14	15	11	26
£48,000-£63,999	19	23	25	13
£64,000-£95,999	11	11	12	11
More than £96,000	8	7	9	5
	Type 1 Group (n=434)	**Control Group (n=751)**	**Type 2 Group (n=373)**	**YouGov (Nov, 2018)[4]**
Political Support**				
Conservative Party	38	43	40	39
Labour Party	39	34	36	36
Liberal Democrats	10	11	11	8
Other/Independent	13	12	13	14
Education***				
Completed Postgraduate (e.g., Masterate or PhD)	9	8	13	
Completed undergraduate (e.g., Bachelor's Degree)	26	27	26	
Some tertiary education (e.g., Certificate or Diploma)	16	17	19	
Trade or Technical Qualification (e.g., Apprenticeship, Industry Qualification, etc.)	14	15	13	
Graduated Secondary School (High School)	32	30	27	
Graduated Primary School (Elementary School)	3	3	2	
Location***				
More than 5 million people (Major Urban Area)	8	8	8	
1 million to 4.9 million people	6	5	6	
100,000 to 999,999 people	21	17	18	
50,000 to 99,999 people	12	16	15	
10,000 to 49,999 people	23	23	23	
1,000 to 9,999 people	20	20	17	
200 to 999 people	5	7	7	
Less than 200 people (Rural Area)	6	4	5	

UK Demographic data sources are reported in earlier in Section 2.5
*Census data for age is calculated as the proportion of the 18 - 80 age group.
**Political support is calculated excluding invalid responses.
***Population data for Education and Location are based on international comparisons rather than on UK census categories, so comparable national statistics are not available. However, the sample shows a satisfactory demographic spread that is consistent between subgroups. Additionally, the univariate and multivariate tests (Table 28 and 29) indicate that neither variable has a statistically significant impact on participant responses. Therefore, any differences between the samples and the UK population are unlikely to impact the generalisability of the study.

3.5.3. Measures

Concept evaluation time is recorded in seconds and aggregated across the six concepts. Time spent answering the additional quiz items in the Type 2 treatment is excluded.

Comparisons of mean concept evaluation times indicate the manipulations successfully encouraged participants to respond using fast Type 1 processing or slow Type 2 processing (Table 21). Since extreme values can influence the mean statistic, we also report the 5% trimmed mean as an added robustness check. The trimmed mean shows over a 40% difference (1 min 59 s) between the time taken by the Type 1 and Type 2 groups. A non-parametric Kruskal-Wallis test for differences in concept evaluation times reveals a statistically significant difference between treatments ($\chi^2(2)$ = 47.887, $p < 0.001$). Post hoc tests show participants in the Type 2 treatment group take significantly longer in the concept evaluation task than participants in the Type 1 treatment ($p < 0.001$) and the control treatment ($p < 0.001$). However, no significant differences are identified between the Type 1 and Control treatments ($p = 0.305$).

Attribute associations are coded as '1 = associated or '0 = not associated' for each attribute-technology combination. Kendal Tau-B nonparametric correlations are used to identify and remove duplicate measures of overlapping memory (attribute) associations that substantially exceed the average (Romaniuk, 2013). As found in Carlisle et al. (2020) and Wright et al. (2014) the attributes *beneficial* and *unpredictable* exceed the 0.30 threshold proposed by Cohen (1988) to differentiate small and medium effect sizes and are therefore removed from further analysis (Table 26).

To enable statistical comparisons between treatment groups, a net positive association variable is calculated as the sum of *each* participants' positive associations minus the sum of their negative associations. Net positive variables are aggregated by CDR (M = -0.25, SD = 4.14), SRM (M = -3.01, SD = 3.75), or combined across all six technologies (M = -3.26, SD = 6.49), with 0 representing an equal balance of positive and negative attribute associations. An overall net positive metric is also reported for each treatment (Table 23) and is calculated as the sum of *all* participants' positive associations for each technology, minus their negative associations, converted to an overall percentage. The statistical properties of the net positive variables are examined by treatment group (Table 27*;* Figures 19, 20, and 21) and deemed acceptable for further analysis. Univariate and multivariate tests between the *Combined net positive variable* and demographic variables are conducted to identify covariates for the principal analysis. Univariate tests (Table 28) identify statistically significant relationships between the combined net positive variable and age across all three treatments and political party in the control treatment. However, multivariate analysis including tests for main effects and two-way interactions are non-significant (Table 29). Therefore, demographic covariates are deemed unnecessary for further statistical tests.

Further questions include participant confidence in their understanding of the stimuli and prior awareness of the technologies. For each technology, participants indicate their confidence in understanding on a five-point Likert-style scale ("after reading the description I think that I could explain [this technology] to somebody else") coded as 1 = Strongly agree and 5 = Strongly disagree. Participants in the *Type 2* treatment were overall slightly more confident in their understanding (M = 2.65, SD = 0.78) than participants in the *Type 1* (M = 2.71, SD = 0.80) or *Control* treatments (M = 2.71, SD = 0.80); however, the differences between treatments are non-significant ($F_{(.05, 2, 1555)}$ = 0.95, p = 0.39). Following the concept evaluation block participants are asked "Did you know about any of these proposals before you began this survey?". Responses are coded as '1 = yes', '0 = no' (M = 0.19, SD = 0.39).

3.5.4. Nonparametric correlations test for overlapping mental constructs

Table 26: Kendall Tau-b nonparametric correlations (n=1558)

	Unk	Unp	Ris	Art	Qui	Eye	Und	Ben	Con	Env	Sus	Cos
Unknown effects		0.34	0.27	0.17	0.00	0.05	-0.13	-0.24	-0.20	-0.21	-0.19	-0.16
Unpredictable*	0.34		0.32	0.20	0.02	0.05	-0.13	-0.25	-0.21	-0.22	-0.20	-0.16
Risky	0.27	0.32		0.22	0.02	0.08	-0.15	-0.24	-0.21	-0.23	-0.20	-0.14
Artificial	0.17	0.20	0.22		0.08	0.13	-0.02	-0.13	-0.07	-0.13	-0.10	-0.08
Quick Fix	0.00	0.02	0.02	0.08		0.05	-0.02	-0.03	0.00	-0.03	-0.04	0.01
Eyesore	0.05	0.05	0.08	0.13	0.05		-0.02	-0.05	-0.03	-0.07	-0.04	-0.02
Understandable	-0.13	-0.13	-0.15	-0.02	-0.02	-0.02		0.21	0.21	0.20	0.17	0.10
Beneficial*	-0.24	-0.25	-0.24	-0.13	-0.03	-0.05	0.21		0.26	0.32	0.30	0.18
Controllable	-0.20	-0.21	-0.21	-0.07	0.00	-0.03	0.21	0.26		0.25	0.25	0.16
Env. Friendly	-0.21	-0.22	-0.23	-0.13	-0.03	-0.07	0.20	0.32	0.25		0.27	0.18
Sustainability	-0.19	-0.20	-0.20	-0.10	-0.04	-0.04	0.17	0.30	0.25	0.27		0.19
Cost effective	-0.16	-0.16	-0.14	-0.08	0.01	-0.02	0.10	0.18	0.16	0.18	0.19	

*Unpredictable and Beneficial were both correlated with other attributes and were therefore removed.

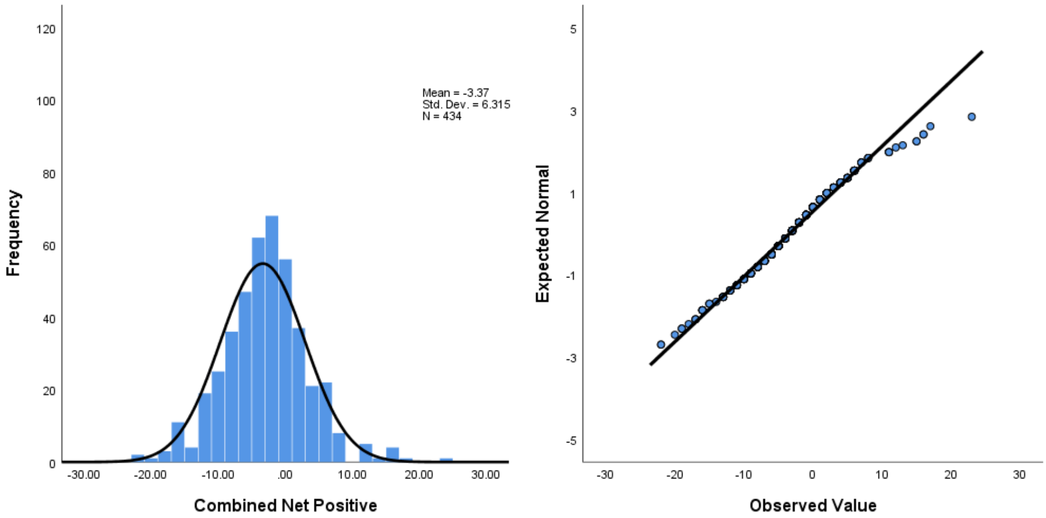
3.5.5. Net positive variable statistics

Table 27: Net positive variable statistics

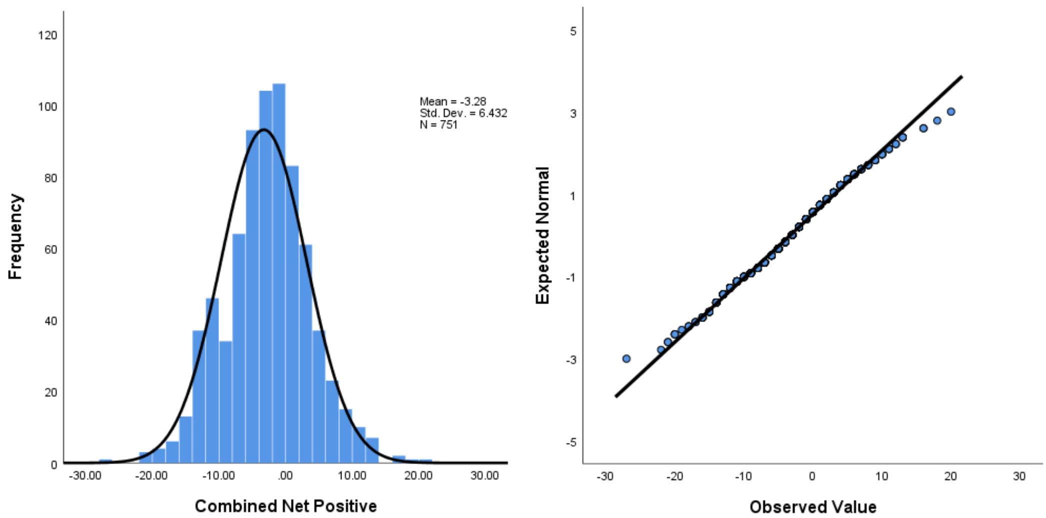
	M	SD	Max	Min	Skewness	Kurtosis
Combined Net Positive						
Type 1	-3.37	6.32	23.00	-22.00	0.23	1.22
Control	-3.28	6.43	20.00	-27.00	0.00	0.48
Type 2	-3.09	6.83	21.00	-29.00	-0.36	1.69
CDR Net Positive						
Type 1	-0.24	4.06	13.00	-12.00	0.07	0.36
Control	-0.30	4.21	13.00	-14.00	0.21	0.23
Type 2	-0.14	4.11	11.00	-15.00	-0.31	0.69
SRM Net Positive						
Type 1	-3.13	3.74	14.00	-13.00	0.46	0.65
Control	-2.98	3.68	9.00	-13.00	0.16	-0.01
Type 2	-2.94	3.89	10.00	-14.00	0.14	0.54

Figure 19: Combined net positive associations – Distribution and Q-Q plots

Type 1 treatment



Control treatment



Type 2 treatment

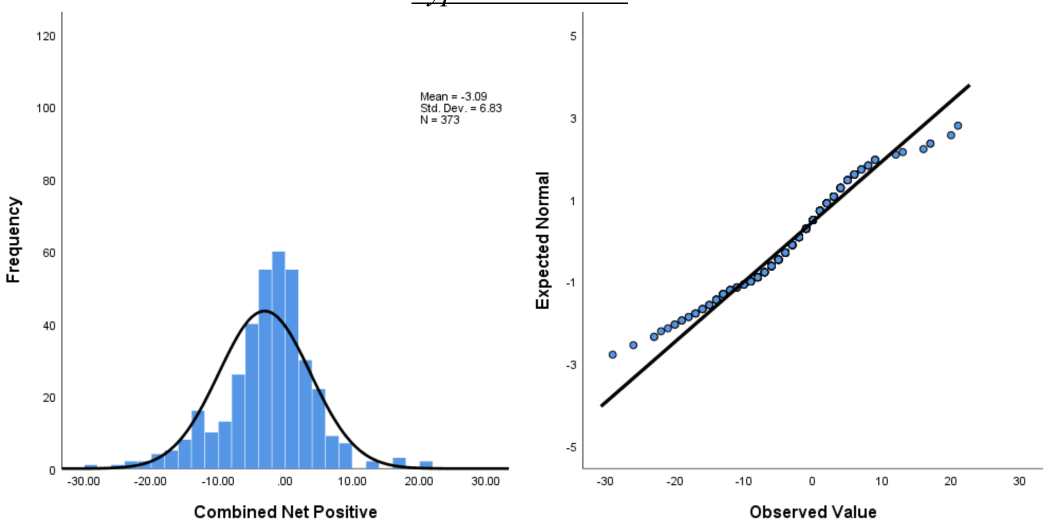
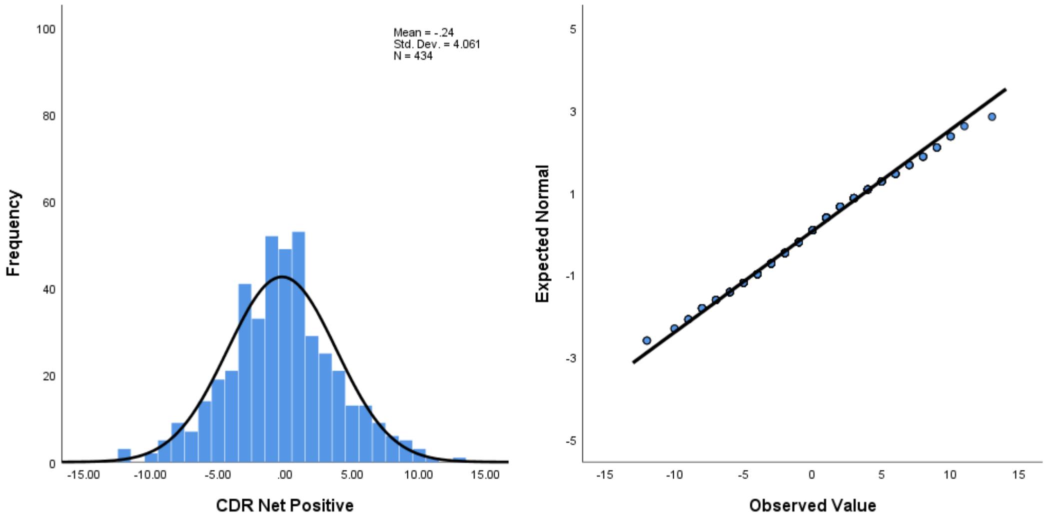
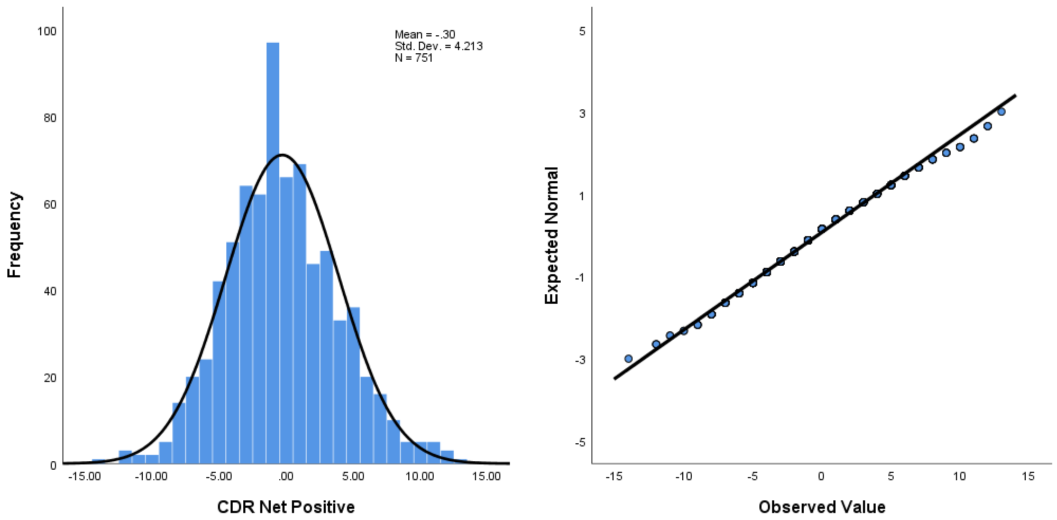


Figure 20: CDR net positive associations – Distribution and Q-Q plots

Type 1 treatment



Control treatment



Type 2 treatment

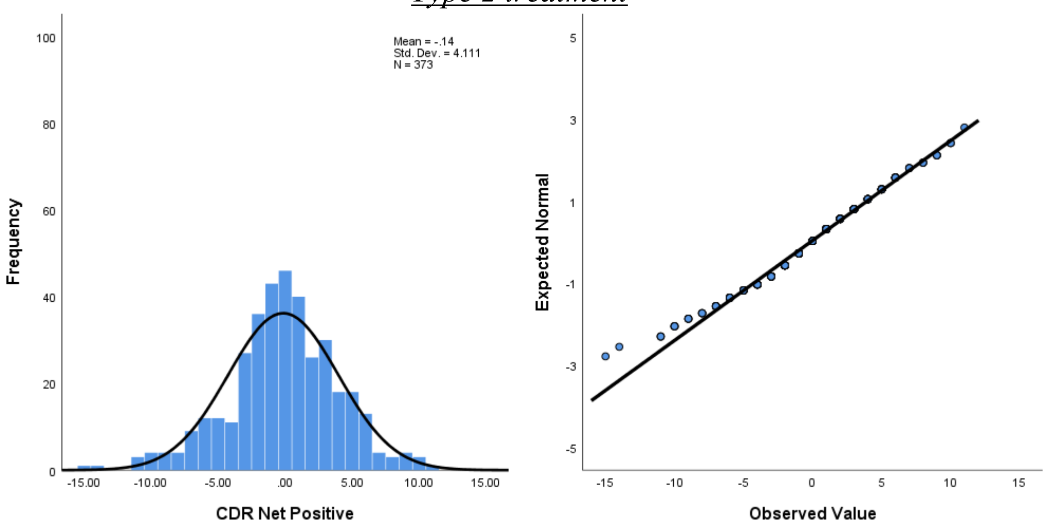
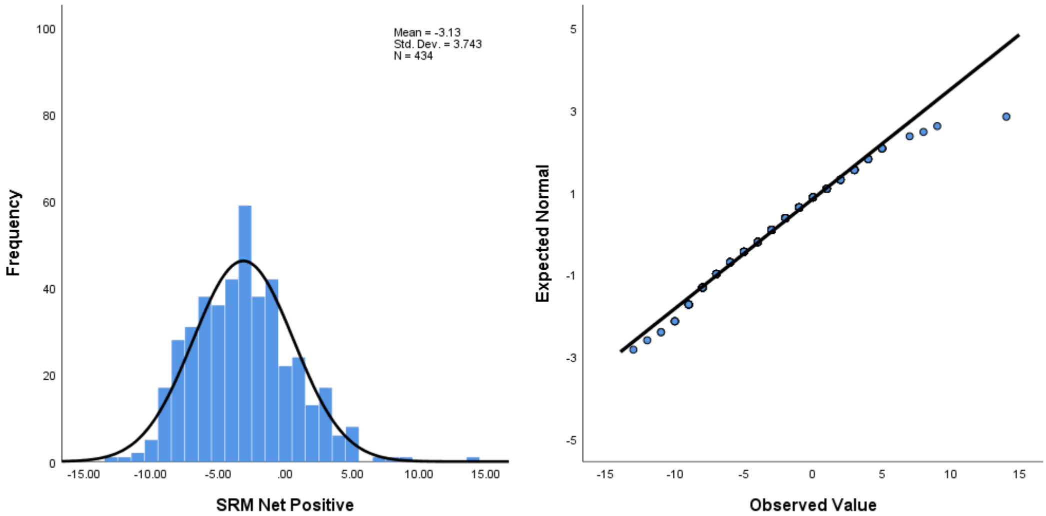
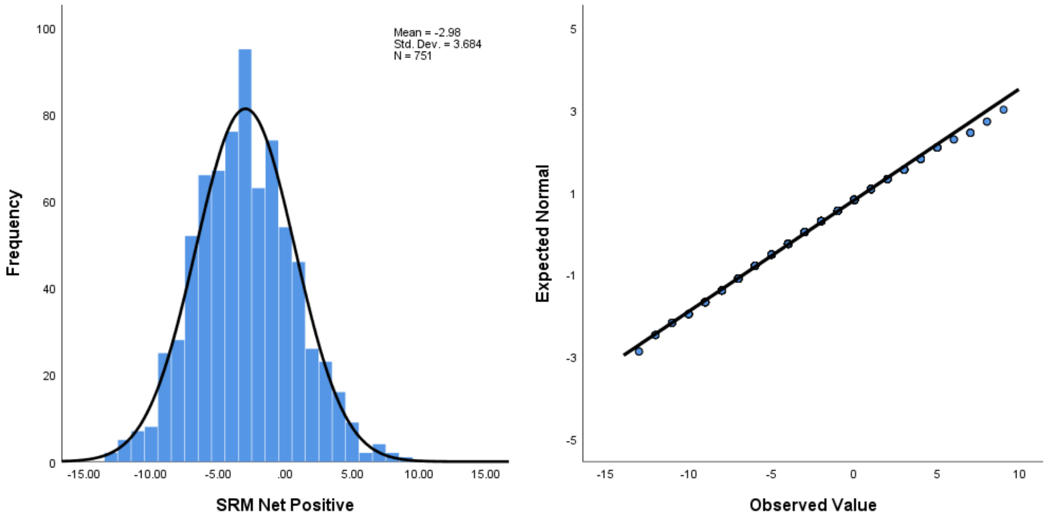


Figure 21: SRM net positive associations – Distribution and Q-Q plots

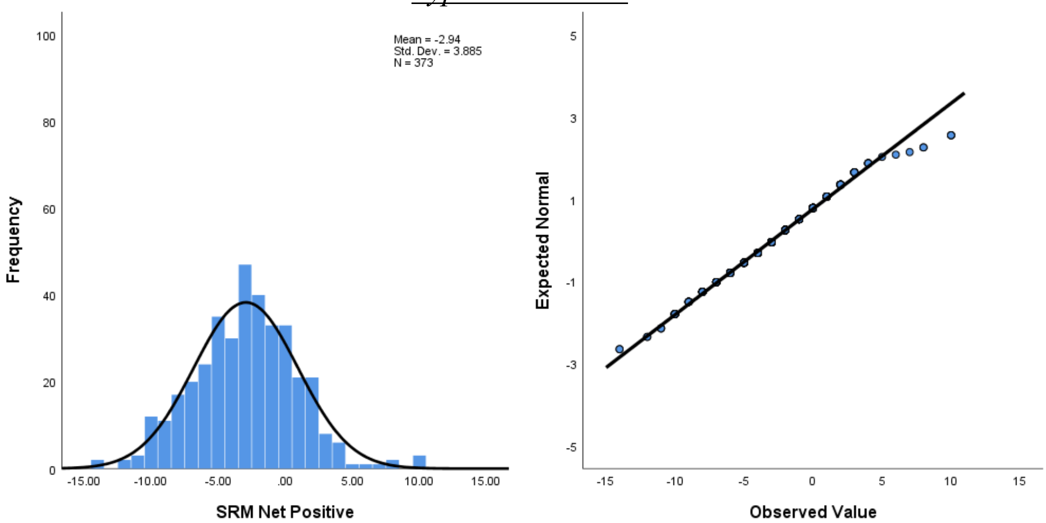
Type 1 treatment



Control treatment



Type 2 treatment



3.5.6. Univariate tests

Table 28: Univariate tests for differences on the net positive variable

		Test statistic	Test statistic value	P value	Bonferroni-corrected critical P value
Combined Sample					
Gender	One Way Anova	$\mathbf{F}_{(.05, 1, 1556)}$	0.223	0.637	0.008
Location	One Way Anova	$\mathbf{F}_{(.05, 7, 1550)}$	3.115	0.003	0.008
Education	One Way Anova	$\mathbf{F}_{(.05, 5, 1552)}$	2.691	0.020	0.008
Household Income	One Way Anova	$\mathbf{F}_{(.05, 8, 1549)}$	0.858	0.552	0.008
Political Party	One Way Anova	$\mathbf{F}_{(.05, 6, 1551)}$	7.146*	0.000	0.008
Age	Correlation	$\mathbf{r}$	-0.188*	0.000	0.008
Type 1 Treatment					
Gender	One Way Anova	$\mathbf{F}_{(.05, 1, 432)}$	0.494	0.482	0.008
Location	One Way Anova	$\mathbf{F}_{(.05, 7, 426)}$	1.559	0.146	0.008
Education	One Way Anova	$\mathbf{F}_{(.05, 5, 428)}$	1.789	0.114	0.008
Household Income	One Way Anova	$\mathbf{F}_{(.05, 8, 425)}$	0.295	0.967	0.008
Political Party	One Way Anova	$\mathbf{F}_{(.05, 6, 427)}$	2.071	0.056	0.008
Age	Correlation	$\mathbf{r}_{(432)}$	-0.209*	0.000	0.008
Control Treatment					
Gender	One Way Anova	$\mathbf{F}_{(.05, 1, 749)}$	0.017	0.895	0.008
Location	One Way Anova	$\mathbf{F}_{(.05, 7, 743)}$	1.520	0.157	0.008
Education	One Way Anova	$\mathbf{F}_{(.05, 5, 745)}$	2.357	0.039	0.008
Household Income	One Way Anova	$\mathbf{F}_{(.05, 8, 742)}$	1.682	0.099	0.008
Political Party	One Way Anova	$\mathbf{F}_{(.05, 6, 744)}$	4.054*	0.001	0.008
Age	Correlation	$\mathbf{r}_{(749)}$	-0.138*	0.000	0.008
Type 2 Treatment					
Gender	One Way Anova	$\mathbf{F}_{(.05, 1, 371)}$	3.287	0.071	0.008
Location	One Way Anova	$\mathbf{F}_{(.05, 7, 365)}$	2.253	0.030	0.008
Education	One Way Anova	$\mathbf{F}_{(.05, 5, 367)}$	1.275	0.274	0.008
Household Income	One Way Anova	$\mathbf{F}_{(.05, 8, 364)}$	0.748	0.649	0.008
Political Party	One Way Anova	$\mathbf{F}_{(.05, 6, 366)}$	1.896	0.081	0.008
Age	Correlation	$\mathbf{r}_{(371)}$	-0.256	0.000	0.008

*indicates significance at the Bonferroni-corrected critical P value of .008

3.5.7. Multivariate tests

Table 29: Multivariate tests for differences on the net positive variable

	F value	P value	Bonferroni- corrected critical P value
Combined Sample (*n* = 1558)			
1 Intercept	1.284	0.257	0.002
2 Gender	1.477	0.225	0.002
3 Location	1.233	0.281	0.002
4 Education	1.056	0.383	0.002
5 Household Income	0.955	0.470	0.002
6 Political Party	1.455	0.191	0.002
7 Age	0.373	0.541	0.002
2×3 Interaction	0.747	0.632	0.002
2×4 Interaction	1.152	0.331	0.002
2×5 Interaction	0.614	0.766	0.002
2×6 Interaction	1.271	0.268	0.002
2×7 Interaction	0.000	0.988	0.002
3×4 Interaction	0.712	0.894	0.002
3×5 Interaction	0.737	0.926	0.002
3×6 Interaction	1.025	0.429	0.002
3×7 Interaction	0.586	0.767	0.002
4×5 Interaction	1.110	0.298	0.002
4×6 Interaction	1.115	0.306	0.002
4×7 Interaction	0.660	0.654	0.002
5×6 Interaction	0.796	0.839	0.002
5×7 Interaction	1.688	0.097	0.002
6×7 Interaction	0.916	0.483	0.002
Control Treatment (*n* = 751)			
1 Intercept	0.067	0.796	0.002
2 Gender	0.459	0.499	0.002
3 Location	0.308	0.950	0.002
4 Education	0.240	0.945	0.002
5 Household Income	0.689	0.701	0.002
6 Political Party	0.908	0.489	0.002
7 Age	0.001	0.969	0.002
2×3 Interaction	0.431	0.883	0.002
2×4 Interaction	0.427	0.830	0.002
2×5 Interaction	0.430	0.903	0.002
2×6 Interaction	0.862	0.507	0.002
2×7 Interaction	0.603	0.438	0.002
3×4 Interaction	0.877	0.664	0.002
3×5 Interaction	0.571	0.994	0.002
3×6 Interaction	0.847	0.717	0.002
3×7 Interaction	0.445	0.873	0.002
4×5 Interaction	1.102	0.317	0.002
4×6 Interaction	0.825	0.700	0.002
4×7 Interaction	0.173	0.972	0.002
5×6 Interaction	0.810	0.787	0.002
5×7 Interaction	0.669	0.719	0.002
6×7 Interaction	1.314	0.257	0.002

Type 1 Treatment (*n* = 434)			
1 Intercept	0.179	0.672	0.002
2 Gender	0.153	0.696	0.002
3 Location	1.098	0.367	0.002
4 Education	1.336	0.252	0.002
5 Household Income	1.341	0.227	0.002
6 Political Party	0.336	0.917	0.002
7 Age	0.974	0.325	0.002
2×3 Interaction	0.648	0.716	0.002
2×4 Interaction	0.563	0.690	0.002
2×5 Interaction	0.762	0.637	0.002
2×6 Interaction	2.389	0.053	0.002
2×7 Interaction	0.164	0.686	0.002
3×4 Interaction	1.080	0.369	0.002
3×5 Interaction	0.837	0.761	0.002
3×6 Interaction	1.417	0.090	0.002
3×7 Interaction	1.152	0.334	0.002
4×5 Interaction	0.980	0.501	0.002
4×6 Interaction	1.316	0.190	0.002
4×7 Interaction	1.063	0.377	0.002
5×6 Interaction	1.175	0.264	0.002
5×7 Interaction	1.476	0.170	0.002
6×7 Interaction	0.382	0.860	0.002
Type 2 Treatment (*n* = 373)			
1 Intercept	0.023	0.881	0.002
2 Gender	0.013	0.910	0.002
3 Location	1.348	0.237	0.002
4 Education	2.223	0.058	0.002
5 Household Income	0.965	0.468	0.002
6 Political Party	0.883	0.510	0.002
7 Age	0.001	0.982	0.002
2×3 Interaction	1.295	0.267	0.002
2×4 Interaction	1.720	0.152	0.002
2×5 Interaction	0.469	0.855	0.002
2×6 Interaction	0.709	0.588	0.002
2×7 Interaction	0.128	0.721	0.002
3×4 Interaction	1.526	0.072	0.002
3×5 Interaction	1.603	0.026	0.002
3×6 Interaction	1.865	0.017	0.002
3×7 Interaction	1.571	0.164	0.002
4×5 Interaction	1.224	0.234	0.002
4×6 Interaction	1.268	0.234	0.002
4×7 Interaction	1.933	0.111	0.002
5×6 Interaction	1.434	0.103	0.002
5×7 Interaction	1.114	0.361	0.002
6×7 Interaction	0.172	0.972	0.002

3.5.8. Attribute popularity (salience) split by CDR and SRM

The main manuscript reports the ranked attributes by popularity as an aggregate across the six CDR and SRM technologies. As there are substantial differences in perceptions between CDR and SRM technologies, Table 30 and Table 31 report the same data, split by class of technique. The percentage share of associations varies between CDR and SRM technologies but is remarkably consistent across treatments (see error bars, Table 30 and Table 31). In line with previous research (Carlisle et al., 2020; Wright et al., 2014) the negative attributes *unknown effects* and *risky,* rank the highest by popularity (salience) and account for approximately 30% of the total CDR attribute associations and approximately 45% of the total SRM attribute associations.

Table 30: Attribute popularity for CDR approaches, as % of associations

Rank	Attribute	Type 1	Control	Type 2
1	Unknown effects	17	18	17
2	Risky	12	13	14
3	Understandable	10	11	11
4	Environmentally friendly	11	11	11
5	Controllable	10	10	11
6	Long-term sustainability	10	10	10
7	Artificial	9	10	10
8	Cost effective	6	6	6
9	Eyesore	6	6	6
10	Quick-fix	7	5	5

Mean (Error bars show range between treatments)

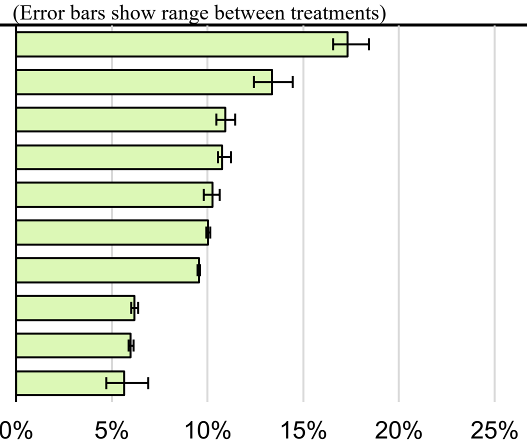
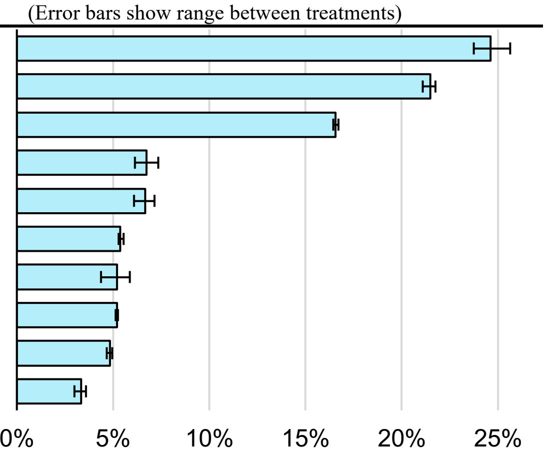


Table 31: Attribute popularity for SRM approaches, as % of associations

Rank	Attribute	Type 1	Control	Type 2
1	Unknown effects	24	26	24
2	Risky	21	22	22
3	Artificial	17	16	17
4	Understandable	7	6	7
5	Quick-fix	7	7	6
6	Environmentally friendly	6	5	5
7	Eyesore	5	4	6
8	Controllable	5	5	5
9	Long-term sustainability	5	5	5
10	Cost effective	3	4	3

Mean (Error bars show range between treatments)



ARTICLE 3:
PUBLIC RESPONSE TO DECARBONISATION THROUGH ALTERNATIVE SHIPPING FUELS

Preface:

This chapter contains work submitted to a journal for peer review.

The full article and supplementary information are reproduced in the following chapter. While the article structure and content are preserved, some minor changes are made to ensure consistency across this thesis. The reference list is also aggregated at the end of the thesis.

This project has been evaluated by peer review and judged to be low risk (4000024836)

Summary:

Aim: Measure UK public perceptions of six alternative shipping fuels.

Main Research Question:

RQ3.1 What are the UK public's perceptions of alternative shipping fuels?

Method: Mixed method, involving qualitative depth interviews (UK convenience sample; n = 13) and self-administered survey (UK panel sample; n = 30), followed by a large-scale quantitative survey (UK; n = 992).

Findings: Respondents prefer biofuels and hydrogen, followed by liquid natural gas. Nuclear and heavy fuel oil are disliked, although nuclear is preferred to heavy fuel oil, and ammonia is the least favoured. Participants living near ports are somewhat more supportive of alternative fuels.

Contributions: The research is the first to investigate public perceptions of alternative shipping fuels, initiating and providing a baseline for ongoing research into the topic. The findings provide timely and critical feedback on public perceptions of alternative shipping fuels to inform ongoing research, development, and policy on climate solutions and pathways to decarbonisation. The mixed-method approach provided richer insights into the drivers behind perceptions of alternative fuels and demonstrates – for the first time – the value of incorporating qualitative insights with this quantitative technique.

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Daniel Carlisle
Name/title of Primary Supervisor:	Prof. Malcolm Wright
Name of Research Output and full reference:	
Carlisle, D. P., Feetham, P. M., Wright, M. J., & Teagle, D. A. H. (Unpublished) Public response to decarbonisation through alternative shipping fuels	
In which Chapter is the Manuscript /Published work:	4
Please indicate:	
• The percentage of the manuscript/Published Work that was contributed by the candidate:	60%
and	
• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
Daniel led the research design, fieldwork, data analysis and drafting the article.	
For manuscripts intended for publication please indicate target journal:	
Climatic Change	
Candidate's Signature:	
Date:	02-Jun-2022
Primary Supervisor's Signature:	Wright, Malcolm Digitally signed by Wright, Malcolm Date: 2022.06.01 14:36:32 +12'00'
Date:	1-Jun-2022

(This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis)

4.0 Public response to decarbonisation through alternative shipping fuels

Abstract: The international shipping industry is exploring use of carbon-neutral fuels to help eliminate greenhouse gas emissions by 2050. However, the public acceptability of alternative shipping fuels remains unknown. Here we examine UK public perceptions for six shipping fuels using a mixed-method approach. Respondents strongly dislike ammonia, perceived as *unproven*, *risky,* and lacking *availability*. Despite lingering stigma, nuclear is preferred over the incumbent heavy fuel oil, though both are perceived negatively. Perceptions of liquid natural gas are somewhat positive, suggesting that it provides an acceptable near-term option while other fuels are developed. Biofuels and hydrogen are clearly favoured, owing to biofuel's perceived low risk and hydrogen's lack of negative by-products. A third support use of alternative shipping fuels, with support greater from those living near ports - a "yes in my back yard" (YIMBY) effect. The results demonstrate the need for ongoing public engagement to identify societally acceptable decarbonisation pathways.

Key Words: Alternative Fuels, Shipping, Public Engagement, Hydrogen, Ammonia

4.1. Introduction

The 2021 *Call to Action for Shipping Decarbonisation*, signed by 230 maritime industry leaders, sets the ambitious target of reaching net-zero emissions by 2050 (*Call to Action for Shipping Decarbonization*, 2021). To this end, major players are establishing the first Green Corridors (zero emission trade routes) to catalyse decarbonisation of the shipping industry ("All hands on deck," 2022; Getting to Zero Coalition, 2021). Shipping is an efficient mode for transporting goods and currently accounts for 80-90% of world trade (Balcombe et al., 2019; T. W. P. Smith et al., 2014). However, the large amount of energy required to propel vessels across the world is also responsible for 2-3% of global greenhouse gas emissions (Faber et al., 2021; T. W. P. Smith et al., 2014), with additional pollutants including particulate matter and nitrogen and sulphur oxides (McKinlay, Turnock, & Hudson, 2020). Currently, shipping propulsion is dominated by fossil fuels, such as heavy fuel oil (HFO), and although the industry recognises the need for zero-emission fuels to achieve decarbonisation targets (*Call to Action for Shipping Decarbonization*, 2021; Faber et al., 2021; Getting to Zero Coalition, 2021; IMO, 2018) there are, as yet, no widely adopted zero-carbon solutions.

Among the alternatives to HFO, Liquid natural gas (LNG) is a lower-carbon, lower pollutant option. However, its use requires substantial carbon capture and storage to offset emissions (Eide, Chryssakis, & Endresen, 2013; McKinlay et al., 2020). Other fuels such as hydrogen, ammonia, and nuclear emit no CO_2 at the point of use but raise concerns about their lifecycle emissions during production, storage, and transport, as well as about safety and public acceptance (Balcombe et al., 2019; Eide et al., 2013; McKinlay et al., 2020; Royal Society, 2018, 2020; Serra & Fancello, 2020). Blue and green hydrogen and ammonia production may address issues of lifecycle emissions (Royal Society, 2018, 2020). Biofuels could also deliver net-zero emissions, provided the supply chain is also carbon-neutral (Balcombe et al., 2019; Horvath, Fasihi, & Breyer, 2018; Kesieme, Pazouki, Murphy, & Chrysanthou, 2019; Royal Society, 2008; Serra & Fancello, 2020), but have implications for land and water use, food production, and biodiversity (Balcombe et al., 2019; Kesieme et al., 2019; Royal Society, 2008).

Until a clear transitional pathway is established many stakeholders are cautious of investing into research and development due to the substantial investment and infrastructure required. While some investigation into the technical uncertainties of green shipping is underway, it remains unclear whether the public will support alternative shipping fuels, or whether public opposition might quash their deployment.

4.1.1. Public engagement and alternative shipping fuels

Adopting alternative shipping fuels has both economic and environmental consequences that will directly impact the global public. Though a few authors acknowledge the role of public involvement in deployment of alternative shipping fuels (Balcombe et al., 2019; Serra & Fancello, 2020), technological development has proceeded largely in isolation from social concerns. Under normative-democratic principles, citizens have a right to participate in decisions that affect them (Fiorino, 1990; Wilsdon & Willis, 2004). Furthermore, public engagement can help identify publicly acceptable pathways to decarbonisation and help legitimize new technologies (Serra & Fancello, 2020). Without public support, alternative shipping fuels may face substantial challenges, such as public opposition and some nations' bans on nuclear energy. Thus, it is critical the shipping industry investigates alternative fuels that both achieve drastic emission cuts and are acceptable to stakeholders including civil societies (Serra & Fancello, 2020).

Previous research on alternative energy has documented public perceptions ranging from large-scale energy infrastructure projects to small-scale or consumer technologies (Boudet, 2019; Gaede & Rowlands, 2018; L′Orange Seigo, Dohle, & Siegrist, 2014; Liao, Molin, & van Wee, 2017; Poumadère, Bertoldo, & Samadi, 2011; Radics, Dasmohapatra, & Kelley, 2015; Ricci, Bellaby, & Flynn, 2008; Roche, Mourato, Fischedick, Pietzner, & Viebahn, 2010). However, our search of peer-reviewed literature identified no research that specifically examines public perceptions of alternative shipping fuels, highlighting the communication gap between civil society, and academia, industry, and policy.

Using a recently developed mixed-method approach (Carlisle et al., 2020; Carlisle, Feetham, Wright, & Teagle, 2022; Wright et al., 2014), we provide the first, systematic measurement of public perceptions of six alternative shipping fuels: *ammonia, biofuels, heavy fuel oil, hydrogen, liquid natural gas,* and *nuclear*. The study begins with a UK-based qualitative phase including in-depth interviews (n=13) and self-administered surveys (n=30) to explore public perceptions and identify the attributes that non-expert citizens associate with alternative shipping fuels (Carlisle et al., 2020; Hogan, Romaniuk, & Faulkner, 2016; Rogers & Ryals, 2007; Wright et al., 2014). Using these qualitative findings, we designed a large-scale survey (n=992) to systematically measure UK public perceptions of alternative shipping fuels (Carlisle et al., 2020; Romaniuk, 2013; Wright et al., 2014). Drawing on Associative Network Theories of Memory (Anderson & Bower, 1973) and techniques used in market research (Romaniuk, 2013) and public engagement (Carlisle et al., 2020, 2022; Wright et al., 2014), our primary measure models citizens' memory structures by analysing the frequency of respondent associations between each fuel and the attributes identified in the qualitative phase. Throughout the analyses, we cross-examine the findings of the qualitative and quantitative phases to yield richer insights and explore the potential drivers behind public perceptions of the six fuels tested.

4.2. Method

Our research uses a two-stage, mixed-method approach to assess public perceptions of alternative shipping fuels. The methods are established in brand research (Bech-Larsen & Nielsen, 1999; Romaniuk, 2013) and public engagement (Carlisle et al., 2020, 2022; Wright et al., 2014), and begin with a qualitative phase to generate and validate measures used in the subsequent quantitative phase. However, our study makes a novel methodological contribution by cross-examining the findings from the two stages in a mixed-method (rather than sequential) approach.

4.2.1. Qualitative phase

The aims of the qualitative phase are twofold: First, we aim to *explore public perceptions of alternative shipping fuels* using qualitative depth interviews (*n*=13). The second aim of the qualitative phase is to *generate a list of attributes that the public associate with alternative shipping fuels* that are used in the quantitative phase as the primary measure of public perceptions. Attributes are generated using two established elicitation techniques (Bech-Larsen & Nielsen, 1999; Carlisle et al., 2020; Rogers & Ryals, 2007; Wright et al., 2014); *Kelley's repertory grid* and selection from a *predetermined list*.

The *Kelley's repertory grid* technique involves comparing similarities and differences between three fuels at a time and was administered during the depth interviews. The *pre-determined list* technique was collected using an additional self-administered survey (*n*=30) to cross-validate the findings of the first technique.

Depth-interviews were conducted using Zoom video conferencing software and the materials were designed and administered virtually using the Qualtrics survey platform and the share-screen function. Lay-participants were recruited using convenience and snowball sampling and achieved a satisfactory demographic spread (Table 33). Each phase is sampled separately and contains unique participants. The interviews begin with a brief introduction to the topic and some open-ended warm-up questions. Participants then read short paragraphs about six fuels. Descriptions (Section 4.5) were based on peer-reviewed literature (Balcombe et al., 2019; Eide et al., 2013; Kesieme et al., 2019; McKinlay et al., 2020; Royal Society, 2008, 2018, 2020), designed using strict matching criteria, reviewed for scientific accuracy, and pre-tested for comprehensiveness. Next, in the Kelley's repertory grid task, participants are asked to compare three fuels at a time and explain why two fuels are similar, but different from the third. The materials are designed so that each fuel appears three times and randomisation is used to avoid order effects. Participants are also asked what "important qualities" they would consider if they had to choose a fuel to implement. The survey finishes with further open-ended questions and demographics. Interview transcripts were analysed using NVivo to identify common themes and generated a list of 43 attributes associated with alternative shipping fuels.

The pre-determined list technique used a self-administered survey design with participants drawn from panel provider *Dynata* (*n*=30). The survey begins with demographics and screening questions, followed by a brief introduction to the topic and warm-up questions. Next, participants read short paragraphs about the six fuels and select which attributes they associate with each fuel. 31 predetermined attributes (separate to those generated in the depth-interviews) were identified through content analysis of ten peer-reviewed articles on alternative shipping fuels, published between 2019 and 2020. A gender quota ensured an even gender split and analysis indicates a satisfactory spread on the age demographic (Table 33). Following the depth-interviews, the frequencies of participants' memory associations were tabulated and compared against the results of the Kelley's repertory grid method. The cross-analysis by frequency of mentions arrived at a final list of fourteen common attributes, seven positive (*reduces emissions, safe, sustainable, available now, beneficial, shows potential, interesting*), and seven negative (*resource intensive, negative by-products, dangerous, unproven, expensive, risky, challenging*).

4.2.2. Quantitative phase

The main research aim for the quantitative phase is to *assess public perceptions and support for alternative shipping fuels.* Our approach involves a large quantitative survey in the UK (*n*=992) using a commercial panel provider, *Dynata*. The survey follows a similar format to the qualitative survey, beginning with demographics, screening, introduction, and warm-up questions (see Figures 25-27).

Next, we apply a brand metric technique adapted to measure public reactions to emerging technologies (Carlisle et al., 2020, 2022; Wright et al., 2014). The technique allows researchers to compare respondents' perceptions of alternative shipping fuels by examining the memory associations that come to mind when they evaluate each fuel. Participants read descriptions of each fuel (Figure 28, 29) in a randomised order. Using a randomised, multi-choice, pick-any format, respondents are asked to select which of the 14 attributes identified in the qualitative phase they associate with each fuel (Figure 30). Additional questions assess support for research and use, understanding, and prior awareness (Figure 31). The survey concludes with an open comment box (Figure 32).

The data were cleaned to remove incompletes, speeders (participants that spent less than 10 seconds per attribute task on average), and participants that selected no attributes in all six tasks. The final sample (n=992) has satisfactory demographic characteristics compared to population estimates with only a slight under-representation of the 18-34 age brackets (Table 34). To test comprehension, we asked if participants believed they could explain each fuel to someone else. Analysis shows satisfactory comprehension with an average of 43% of participants agreeing and 38% neutral (Table 39). Thus, we conclude the data is acceptable for our research purposes.

4.2.3. Quantitative measures

For each fuel, attribute associations are coded as '1 = associated' or '0 = not associated'. First, we use Kendall Tau-b nonparametric correlations (Table 35) to test for overlapping memory associations (i.e., attributes with similar meanings; Romaniuk, 2013). The attributes *beneficial* and *dangerous* showed substantially higher correlations (>0.35) with the attributes *sustainable* and *risky*, meeting the criteria for removal (Carlisle et al., 2020, 2022; Wright et al., 2014). The remaining analyses were conducted with the 12 retained attributes.

The *net associations* variables are calculated as the sum of each respondent's positive attribute associations minus the sum of their negative attribute associations for each fuel, and as an aggregate across all six fuels. To enable more intuitive comparison between fuels we also calculate a *net* *association metric* as the percentage of positive associations for each fuel, minus the percentage of negative associations (Table 32 and Figure 23).

Table 32: Attribute associations with alternative shipping fuels

	Biofuel	Hydrogen	LNG	Nuclear	HFO	Ammonia	Total
Total Associations	2871	3039	2237	2920	2190	2467	**15724**
Average Associations	2.9	3.1	2.3	2.9	2.2	2.5	**15.9**
Positive Associations	61%	60%	55%	42%	40%	30%	**49%**
Negative Associations	39%	40%	45%	58%	60%	70%	**51%**
Net Associations (%)	**21%**	**20%**	**10%**	**-15%**	**-20%**	**-40%**	**-3%**

Above: The net association measurement reveals biofuels and hydrogen are clearly favoured, while perceptions of liquid natural gas are somewhat positive, suggesting that it provides an acceptable near-term option. Despite lingering stigma, nuclear is preferred over the incumbent heavy fuel oil, though both are perceived negatively. Respondents strongly dislike ammonia.

Next, we examine the statistical properties of the *net association* variables prior to further analyses. The *aggregate net association* variable can take any value between −36 and 36 where '0' represents net-zero associations (i.e., neutral perceptions). The individual *net associations* variables can take any value between -6 and 6. Variable properties are presented in Table 36 and show a close approximation to a normal distribution, indicating they are suitable for further analysis. Univariate tests identify a small, but statistically significant relationships with the *age* variable and the *aggregate net associations* variable, however, multivariate analysis with 2-way interactions does not reveal significant relationships (Table 37). Accordingly, we conclude no covariates are necessary for further statistical tests.

Concept maps are constructed by tabulating the observed attribute counts for each fuel, calculating the chi-square expected attribute counts, then calculating the percentage point deviations between the observed and expected counts (Table 38; Figure 24).

Additional questions are outlined in Figure 31 with analysis reported in Table 39. Prior awareness was coded as '1 = have heard of [fuel] as an alternative shipping fuel'; '2 = have heard of [fuel], but not for shipping'; '3 = have not heard of [fuel]'. Likert questions were coded on a 5-point scale where '1 = Strongly Agree' and '5 = Strongly Disagree' and were truncated to 'Agree', 'Neutral', and 'Disagree' for reporting. To test for the NIMBY effect, we calculate an *average support for use* variable as the mean of the six *support for use* variables for each fuel. Since the variable is an aggregate of several ordinal items, we treat the variable as interval data (Norman, 2010) and deem parametric two-sided statistical tests appropriate.

4.2.4. Mixed-method analysis

Throughout the article we report the results of statistical analyses from the large, quantitative survey. While quantitative research can provide broad, generalisable insights that are representative of a population, the methods lack the ability for the researchers to probe respondents for the "why?" behind their answers. Accordingly, in our mixed-methods approach, we supplement our quantitative findings with insights and direct quotes from participants in the qualitative depth-interviews. We use thematic analysis from the Kelley's repertory grid tasks to understand *why* participants associated certain attributes with each fuel, and therefore obtain a fuller picture of the drivers behind the differences in perceptions of alternative shipping fuels.

4.3. Results

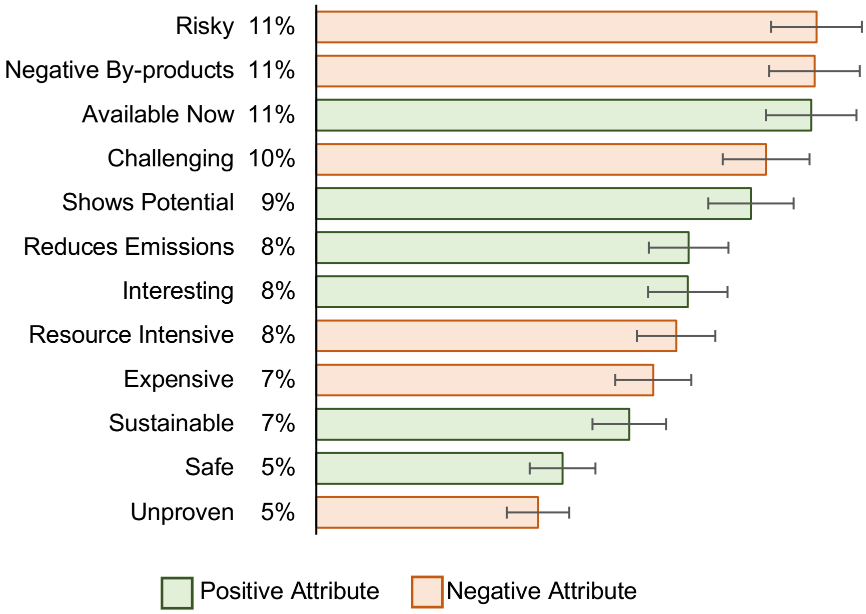
4.3.1. Awareness of alternative shipping fuels

Findings from the qualitative depth-interviews suggest citizens have heard of many of the six fuels but are unaware of their maritime applications. This exploratory finding is quantified in the online survey where on average 58% of participants had heard of each fuel, though only 20% were aware they could be used for shipping (see Table 39).

4.3.2. General perceptions of alternative shipping fuels

The most frequently mentioned attribute associations for alternative maritime fuels are *risky, negative by-products* and *available now* (Figure 22), accounting for a third of the total associations. This indicates that these topics are the most salient concerns of UK citizens.

Figure 22: Percentage share of attribute associations across alternative shipping fuels.



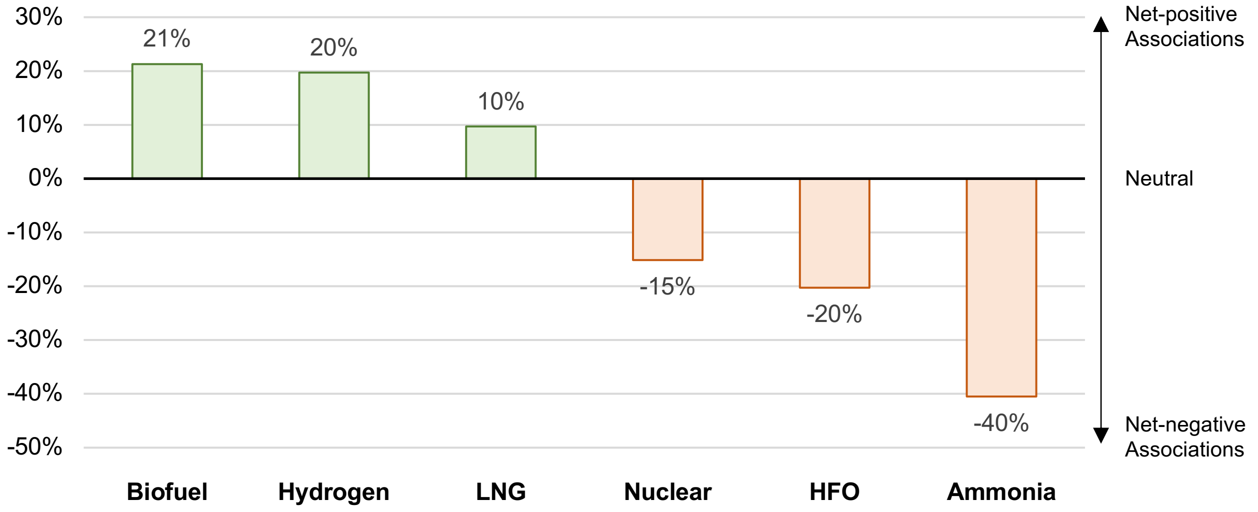
Above: The top three attributes (*risky, negative by-products,* and *available now*) account for a third of all associations. Error bars show standard error.

4.3.3. Comparing perceptions between alternative shipping fuels

To compare perceptions between fuels, we subtract the percentage of negative associations from the percentage of positive associations to produce a 'net-association' metric (see Figure 23 and Table 32). At the aggregate level, respondents' perceptions of alternative shipping fuels are approximately neutral with only 3% more negative associations than positive association. However, there are substantial differences in perceptions between fuels (Figure 23).

Biofuel and hydrogen are clearly preferred with approximately 20% more positive associations than negative associations. LNG is also positively perceived despite being a fossil-fuel. Interestingly, nuclear is favoured over the incumbent HFO; suggesting there is a 'reluctant acceptance' of nuclear energy (Pidgeon, Lorenzoni, & Poortinga, 2008), despite the lingering stigma. Ammonia is strongly disliked by participants with 40% more negative associations than positive associations.

Figure 23: Net associations with alternative shipping fuels.



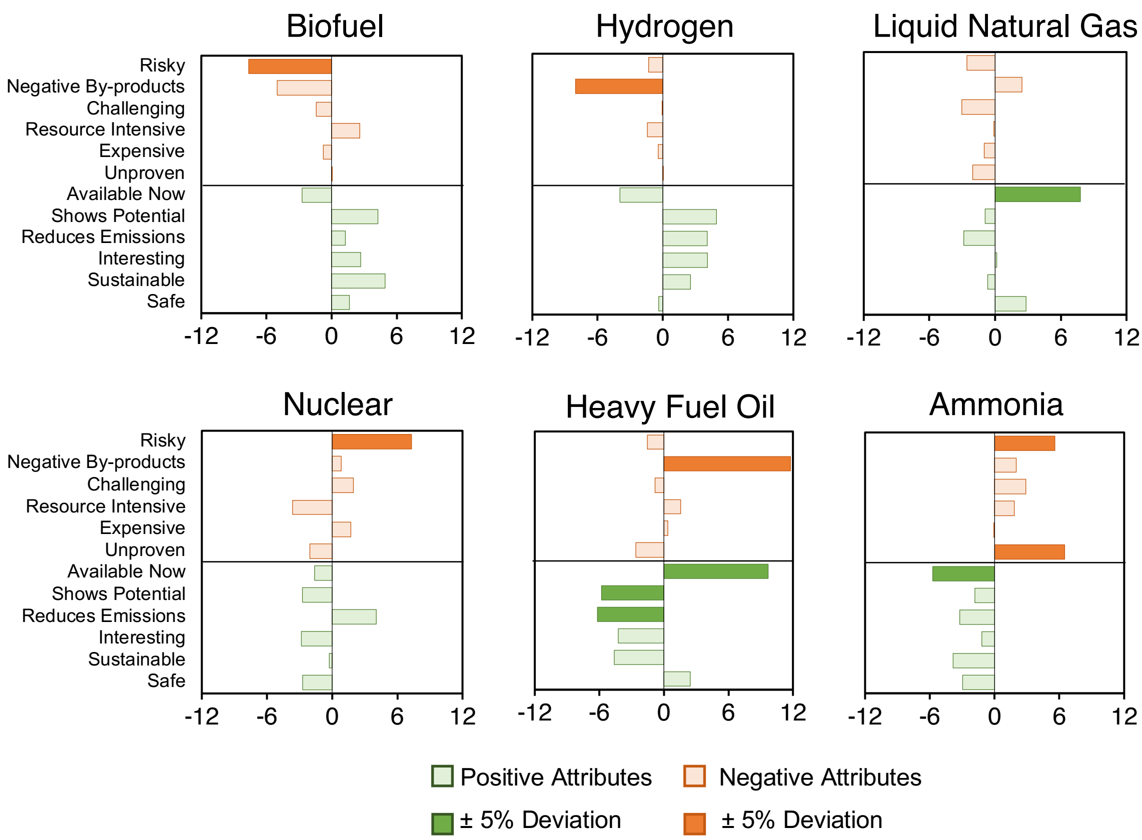
Above: Bars show the net associations (positive associations minus negative associations) for each fuel. Perceptions of biofuel, hydrogen, and LNG are mostly positive, whereas perceptions of nuclear, HFO, and ammonia are mostly negative.

4.3.4. Concept maps

To explore the drivers behind respondents' perceptions we construct concept maps that show how attribute associations differ between fuels. For each fuel we calculate the percentage difference between actual and chi-square expected counts for each attribute (Figure 24; Table 38). This approach controls for baseline associations, so deviations reflect differences in public perception for specific attributes on individual fuels.

Skews (Figure 24) show that the more favourably perceived fuels, *biofuel,* and *hydrogen,* have greater positive associations and fewer negative associations. In contrast, the least favoured fuel, *ammonia*, has fewer positive associations and greater negative associations. This pattern aligns with broader findings from the risk literature that people with favourable perceptions of an activity typically perceive high benefits and low risk (and vice versa; Slovic & Peters, 2006) and is consistent with similar analysis conducted on climate engineering proposals (Carlisle et al., 2020, 2022; Wright et al., 2014). Middling fuels like LNG show little pattern with predominantly small, irregular deviations. However, some noteworthy deviations (greater than ±5 %; dark fill) stand out from the patterns described above, indicating they are a major driver of perceptions for that fuel.

Figure 24: Concept maps for alternative shipping fuels



Above: Negative attributes (orange) and positive attributes (green) are presented in descending order of popularity. Bars show the percentage point deviations between actual and expected attribute associations for each fuel. Positively perceived fuels like biofuel and hydrogen have higher than expected associations with positive attributes and lower than expected associations with negative attributes. Negatively perceived fuels like ammonia show the opposite pattern. Dark fill indicates noteworthy deviations (greater than ± 5%) indicating those attributes contribute heavily to citizens' perceptions.

Biofuels has exceptionally low rates of association with the attribute *risky* (7.6% less than expected) indicating that citizens view biofuels as relatively low risk. This is also reflected in the qualitative depth-interviews with participants remarking *"It feels much safer"* and "*even the name of it sounds softer and greener to the layman"*.

Hydrogen has exceptionally low rates of associations with *negative by-products* (8.0% less than expected) which contributes to its positive perceptions. Findings from the depth-interviews suggests this is due to hydrogen only emitting water at the point of use. For example, one qualitative participant remarked "*Hydrogen only produces water vapor, whereas obviously liquid natural gas produces* CO_2 *and nuclear produces nuclear waste. So, hydrogen doesn't produce anything harmful"*. Another agreed, stating "*with renewable electricity to produce hydrogen, that could be completely emission free"*.

LNG has relatively small deviations, indicating it has few distinctive characteristics and is unlikely to elicit a strong public reaction. The one exception is the high rate of association with the positive attribute *available now* (7.8% more than expected). **HFO** also has similarly high associations with *available now* (9.7% more than expected), however, its overall perception is substantially worse than LNG due to exceptionally high associations with *negative by-products* (11.8% more than expected) and low associations with *reduces emissions* and *shows potential* (6.2% and 5.8% less than expected). For the two currently available fuels, our findings suggest that LNG is preferred over HFO, at least as a short-term transitional fuel.

Nuclear's negative perceptions are largely driven by exceptionally high associations with the attribute *risky* (7.6% more than expected). This is unsurprising given the salience of nuclear disasters noted by participants in the depth-interviews. As one qualitative participant put it; *"if there was an oil spill, it's terrible. But if there's a nuclear spill it's a freaking disaster"*. Another participant added that nuclear shipping *"would probably only take one accident in the world, and that would kill it"*.

Ammonia's strong negative perceptions are driven by several attributes, including high rates of associations with the attributes *unproven* and *risky* (6.5% and 5.6% more than expected) and low rates of associations with *available now* (5.7% less than expected). Participants' dislike for ammonia is also apparent in the qualitative depth-interviews, described as *"dangerous", "toxic", "hazardous",* and *"poisonous"*. One participant described ammonia as "*relatively untested"* stating; *"it's a bit more dangerous, I guess, in the sense that it is corrosive… and toxic, but… there aren't as many safety protocols established"*. Another dismissed ammonia completely, stating; "*I don't think it has anything going for it at all. It looks pretty dreadful to me"*.

The public's strong dislike for ammonia is particularly relevant following a recent techno-economic assessment that labelled Ammonia "one of the most balanced carbon-free fuels" (Stolz, Held, Georges, & Boulouchos, 2022). These findings are a timely reminder for scientists and the shipping industry to consider public concerns alongside techno-economic evaluations of emerging shipping fuels.

4.3.5. Support for research and use

The initial qualitative depth-interviews suggest participants generally support research into alternative shipping fuels, with many motivated by the shipping industry's significant contributions to global emissions and/or the urgent need to address climate change. Some participants thought research could reduce uncertainty around any negative side-effects. To this effect, one participant mentioned *"it has to be something that isn't going to make the problem worse"* and gave the analogy of the *"cure"* being worse than the *"disease"*. Only one of the thirteen interview participants stated they would not support research, instead suggesting we should avoid shipping and shop locally.

These qualitative findings are also reflected in the quantitative stage where participants were asked whether they would support research or use of each fuel (Table 39). Unsurprisingly, research has higher rates of support compared to use. On average, 50% of participants supported research (20% opposed) and 35% supported use (23% opposed).

Support for individual fuels followed a similar pattern to the net associations' metric with approximately two thirds of participants supporting research into hydrogen or biofuels (5 and 8% opposed respectively) and approximately half supporting their use (7 and 10% opposed respectively). In contrast, less than 40% supported research into ammonia or HFO (24 and 35% opposed respectively) and only 21% support their use (31 and 40% opposed respectively).

Previous research on emerging technologies has observed a "not in my backyard" (NIMBY) effect, whereby citizens show stronger opposition to the deployment of new technologies near where they live (Braun, 2017). To establish whether this phenomenon affects alternative shipping fuels, we compared participants *average support for use* between those that reported living near a port, and those that did not. Interestingly, our analysis indicates participants who self-identified that they live near a port are slightly more supportive of using alternative shipping fuels ($t_{947} = -3.563$, $p < 0.001$) suggesting a "yes in my backyard" (YIMBY) effect. We also compared whether living near a port affected participants perceptions using the net associations variable but found no significant difference ($t_{947} = 0.674$, $p = 0.500$). These findings also rule out NIMBY effects for these data.

4.4. Discussion

Using a novel mixed-method approach, our research marks the beginning of academic inquiry into public perceptions of alternative shipping fuels. Though the UK public generally accept the need to decarbonise the shipping industry, their perceptions and support differ substantially between alternative shipping fuels with hydrogen and biofuel eliciting positive responses but ammonia evoking strong negative reactions. With techno-economic assessments highlighting ammonia as a suitable frontrunner for decarbonising the shipping sector (Stolz et al., 2022) it is crucial that scientists and industry consider the public’s concerns. Additionally, it is striking that nuclear was perceived more favourably than the incumbent heavy fuel oil.

The attributes *risky, negative by-products, and available now*, are the most salient across the fuels (Figure 22) and yielded large deviations in associations between fuels (Figure 24) suggesting issues of risk, negative by-products, and availability are top of citizens’ minds. Industry and policy makers therefore need to consider these evaluative attributes during communications; for example, reassuring citizens that risks and negative by-products will be mitigated.

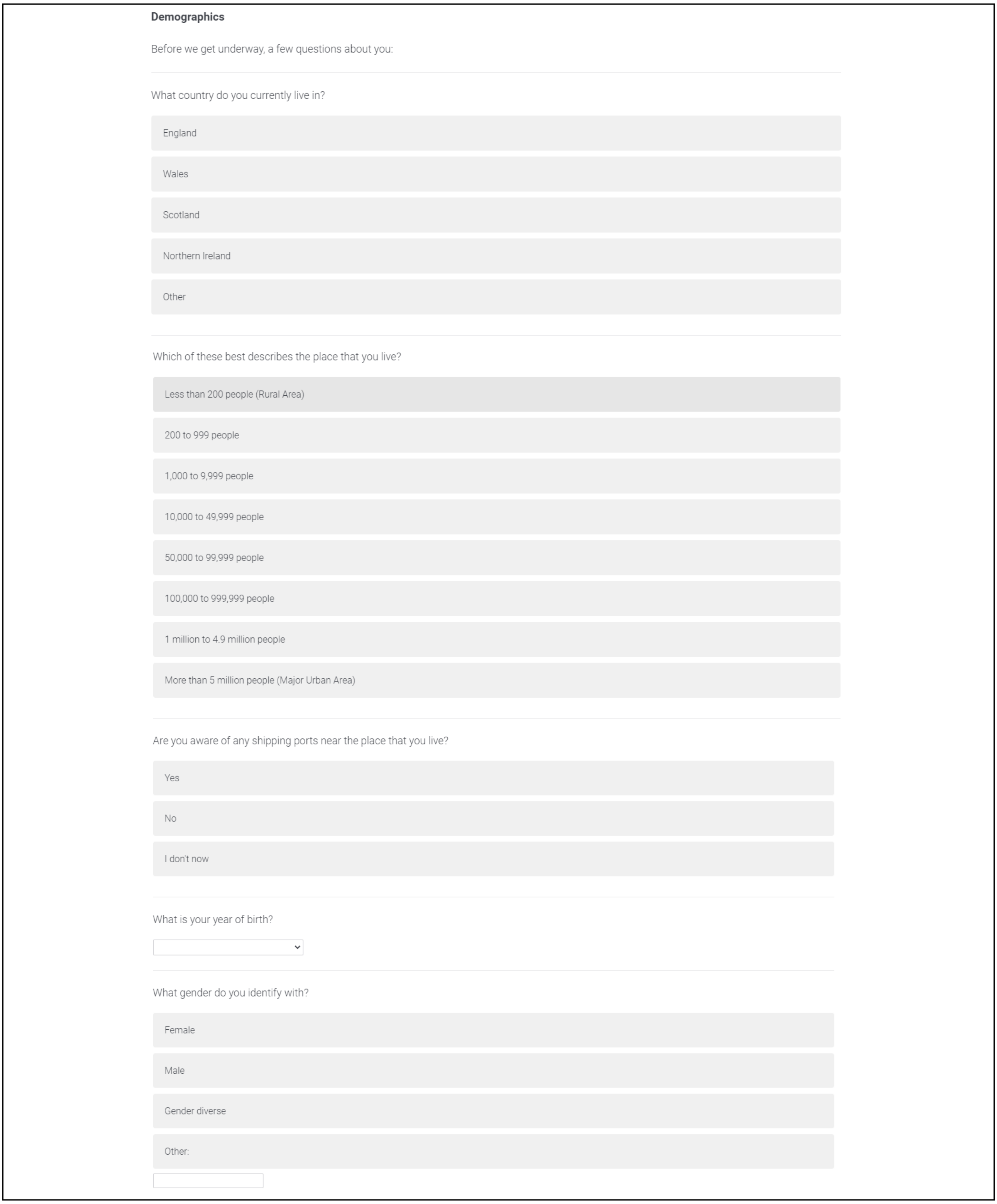
Overall, support for research is higher than support for use, indicating the public would prefer alternative shipping fuels are thoroughly understood before implementation. This finding is promising for researchers, industry, and policy makers who are considering alternative shipping fuels, and highlights the need for increasing research and investment in the field. As one depth-interview participant put it; *“climate change is a pressing issue that needs to be solved as fast as possible, and I think throwing it as much money as possible and as many minds as possible is probably the only solution”.*

Although this research examines public perceptions from the UK, it lays the foundations for a broader research agenda to engage the global public and inform decision making on alternative shipping fuels. As with other emerging technologies, social scientists must be careful to ensure globally diverse perspectives are considered, including indigenous populations and the global south, who are disproportionally affected by climate change and may be the last to benefit from technological improvements. Our research indicates that the public has low awareness of alternative shipping fuels, yet still forms well-considered and, in some cases, strong opinions. Accordingly, as the need to address climate change continues to grow, it is important that industry and policy makers continue open communication and engagement with public to identify acceptable pathways for decarbonising the shipping industry.

4.5. Supplemental materials

The supplementary materials contain detail omitted from the main manuscript, including survey materials, demographic data, and additional analysis.

Figure 25: Demographic block – Quantitative survey



Demographics

Before we get underway, a few questions about you:

What country do you currently live in?

- England
- Wales
- Scotland
- Northern Ireland
- Other

Which of these best describes the place that you live?

- Less than 200 people (Rural Area)
- 200 to 999 people
- 1,000 to 9,999 people
- 10,000 to 49,999 people
- 50,000 to 99,999 people
- 100,000 to 999,999 people
- 1 million to 4.9 million people
- More than 5 million people (Major Urban Area)

Are you aware of any shipping ports near the place that you live?

- Yes
- No
- I don't now

What is your year of birth?

What gender do you identify with?

- Female
- Male
- Gender diverse
- Other:

Figure 26: Introduction and warm-up block – Quantitative survey

Reducing Emissions from Shipping

The shipping sector is one of many industries that are aiming to reduce their emissions. Shipping currently accounts for approximately 2.4% of global greenhouse gas emissions, like carbon dioxide, and also releases pollutants containing nitrogen and sulphur. Most of these emissions come from burning fossil fuels to power ships. As part of ongoing efforts to reduce shipping emissions, the United Nations' International Maritime Organisation released a strategy aiming to phase out greenhouse gas emissions within this century.

One way of phasing out emissions is to switch to alternative fuels with lower emissions. Scientists and engineers have begun initial work to evaluate some of these alternatives, though full implementation is still a long way off.

Please read the statements below and indicate whether you agree or disagree.

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
I would support **research** into alternative shipping fuels.	○	○	○	○	○
The shipping industry should **use** alternative shipping fuels.	○	○	○	○	○

→

Figure 27: Task description block – Quantitative survey

We would like to know what you think about some alternative fuels that the shipping industry could use.

We will show you information about six fuels in the following pages and ask some questions about each one. Please read the description and tick the boxes that you think apply. There are no right or wrong answers; we are interested in your opinion.

→

Figure 28: Fuel descriptions – Quantitative survey

Hydrogen Hydrogen is a non-toxic gas that is already used in a variety of industrial processes. Ships using hydrogen produce no carbon dioxide; instead, the exhaust includes mostly water. Making hydrogen currently requires large amounts of electricity and fossil fuels that produce carbon dioxide emissions. However, if enough renewable electricity becomes available, new methods could produce hydrogen without any greenhouse gas emissions. Hydrogen is unscented and very flammable, so upgrades to existing safety protocols are required.
Ammonia Ammonia is a chemical that is already used to produce fertiliser and cleaners. Ships using ammonia produce no carbon dioxide, but could release pollutants unless exhaust systems are improved. Making ammonia currently requires large amounts of electricity and fossil fuels that produce carbon dioxide emissions. However, if enough renewable electricity becomes available, new methods could produce ammonia without any greenhouse gas emissions. Ammonia is corrosive and toxic and so upgrades to existing safety protocols are required.
Biofuels Biofuels are made from plants that absorb carbon dioxide as they grow. Ships using biofuel release the carbon dioxide back into the atmosphere and could release other pollutants unless exhaust systems are improved. Biofuels need large amounts of land, water, and fertiliser to grow. Biofuels could be made without any greenhouse gas emissions as long as they are grown and processed using renewable sources of energy. Biofuels are biodegradable, however upgrades to existing safety protocols are required.

Figure 29: Fuel descriptions – Quantitative survey (cont.)

Nuclear

Nuclear fuels like uranium are mainly used for producing large amounts of electricity. Ships using nuclear produce no carbon dioxide, but the fuels remain radioactive and require careful disposal after use. Nuclear fuel is produced by mining and refining uranium. Nuclear fuel could be made without any greenhouse gas emissions as long as it is mined and refined using renewable sources of energy. Nuclear fuels raise concerns about distributing radioactive material commercially, so upgrades to existing safety protocols are required.

Heavy Fuel Oil

Heavy fuel oil is a common fuel used for international shipping. Ships using heavy fuel oil will continue to produce carbon dioxide and other pollutants unless exhaust systems are improved. Heavy fuel oil is made from unrefined oil as a by-product of fossil fuel production. Emissions from heavy fuel oil could be offset using technologies that capture and store carbon dioxide. Heavy fuel oil is toxic and non-biodegradable but has well-established safety protocols from decades of use.

Liquid Natural Gas

Liquid natural gas is a common fuel used for heating and cooking. Ships using liquid natural gas will continue to produce carbon dioxide and other pollutants unless exhaust systems are improved. Liquid natural gas is produced as a by-product of fossil fuel production. Emissions from liquid natural gas could be offset using technologies that capture and store carbon dioxide. Natural gas is flammable but has well-established safety protocols from decades of use.

Figure 30: Attribute selection task – Quantitative survey

[Fuel description here]

Please read each of the attributes below and tick the ones that you associate with Heavy Fuel Oil:

Safe	Unproven	Risky
Dangerous	Resource Intensive	Sustainable
Beneficial	Expensive	Negative By-products
Interesting	Challenging	Reduces Emissions
Available Now	Shows Potential	None of These

Figure 31: Additional questions – Quantitative survey

Please read the statements below and indicate whether you agree or disagree.

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
I would support **research** into heavy fuel oil as an alternative shipping fuel	O	O	O	O	O
The shipping industry should **use** heavy fuel oil as an alternative shipping fuel	O	O	O	O	O
After reading the description, I think I could **explain** that Heavy Fuel Oil is an alternative shipping fuel to someone else.	O	O	O	O	O

Before today, had you heard of Heavy Fuel Oil as an alternative fuel?

Please select the statement that that best applies.

I have heard of Heavy Fuel Oil as an alternative shipping fuel.

I have heard of Heavy Fuel Oil as an alternative fuel, but not for shipping.

I have not heard of Heavy Fuel Oil as an alternative fuel.

Figure 32: Final comments block – Quantitative survey

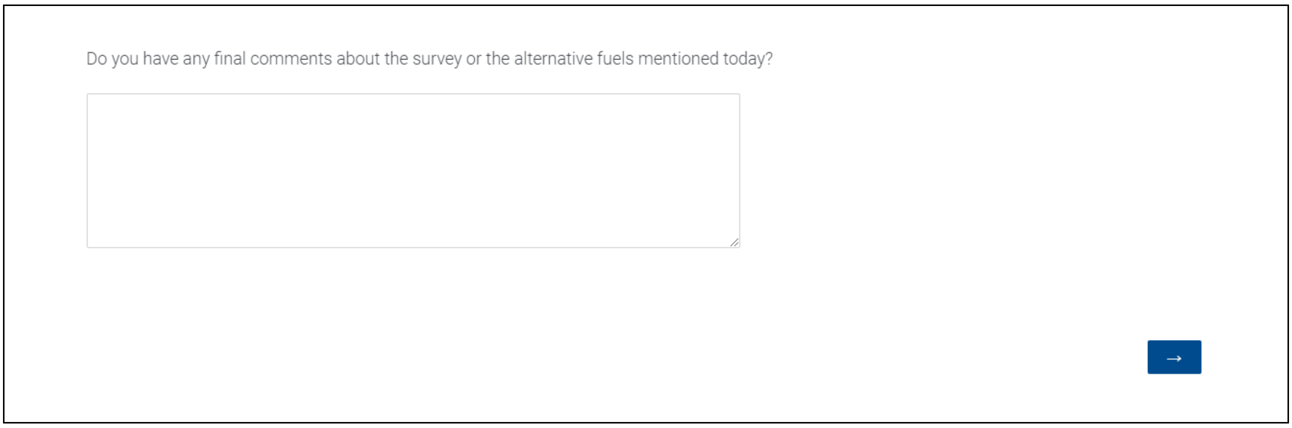


Table 33: Qualitative phase demographics

	Depth Interviews (n = 13)	Self-Administered Survey (n = 30)
Gender		
Male	5	15
Female	8	15
Age (Years)		
18 to 24	2	1
25 to 34	5	4
35 to 44	2	7
45 to 54	2	5
55 to 64	0	8
65 to 74	2	4
75+	0	1

Table 34: Quantitative phase demographics (*n*=992)

	UK Sample	ONS Population Estimate
England	83%	84%
Wales	5%	5%
Scotland	8%	8%
Northern Ireland	4%	3%
	UK Sample	**UK Census**
Age (Years)		
18 - 24	3%	13%
25 - 34	11%	18%
35 - 44	20%	19%
45 - 54	22%	19%
55 - 64	21%	16%
65 - 74	15%	12%
75 - 80	8%	5%
Gender		
Male	54%	49%
Female	46%	51%
Gender Diverse	<1%	-
Non-Binary	<1%	-
Prefer not to say	<1%	-

Table 35: Kendall Tau-b nonparametric correlations

	Red	Saf	Sus	Ava	Ben	Sho	Int	Res	Neg	Dan	Unp	Exp	Ris	Cha
Reduces Emissions		0.10	0.33	0.09	0.31	0.28	0.23	0.03	-0.08	-0.02	-0.01	0.08	0.02	0.11
Safe	0.10		0.21	0.19	0.23	0.11	0.16	-0.01	-0.06	-0.21	-0.08	-0.02	-0.21	-0.07
Sustainable	0.33	0.21		0.08	**0.36**	0.29	0.24	-0.01	-0.15	-0.13	-0.04	0.02	-0.11	0.01
Available Now	0.09	0.19	0.08		0.10	0.04	0.05	0.05	0.18	-0.05	-0.13	0.03	-0.07	0.01
Beneficial*	0.31	0.23	**0.36**	0.10		0.26	0.28	-0.01	-0.14	-0.12	-0.04	0.01	-0.11	0.03
Shows Potential	0.28	0.11	0.29	0.04	0.26		0.33	0.06	-0.14	-0.15	0.02	0.01	-0.11	0.09
Interesting	0.23	0.16	0.24	0.05	0.28	0.33		0.02	-0.16	-0.12	0.02	0.03	-0.10	0.10
Resource Intensive	0.03	-0.01	-0.01	0.05	-0.01	0.06	0.02		0.14	0.02	0.08	0.17	0.03	0.14
Negative By-products	-0.08	-0.06	-0.15	0.18	-0.14	-0.14	-0.16	0.14		0.15	0.02	0.07	0.15	0.06
Dangerous*	-0.02	-0.21	-0.13	-0.05	-0.12	-0.15	-0.12	0.02	0.15		0.09	0.12	**0.41**	0.13
Unproven	-0.01	-0.08	-0.04	-0.13	-0.04	0.02	0.02	0.08	0.02	0.09		0.06	0.14	0.13
Expensive	0.08	-0.02	0.02	0.03	0.01	0.01	0.03	0.17	0.07	0.12	0.06		0.09	0.13
Risky	0.02	-0.21	-0.11	-0.07	-0.11	-0.11	-0.10	0.03	0.15	**0.41**	0.14	0.09		0.17
Challenging	0.11	-0.07	0.01	0.01	0.03	0.09	0.10	0.14	0.06	0.13	0.13	0.13	0.17	

*The attributes *beneficial* and *dangerous* yielded higher than expected correlations (bold) with the attributes *sustainable* and *risky* respectively, and therefore meet the criteria to exclude from further analysis.

Table 36: Variable statistics

	M	SD	Max	Min	Skewness	Kurtosis
Net Association variables						
Combined	-0.46	5.92	25	-20	0.06	1.07
Biofuel	0.62	2.05	6	-5	0.03	-0.15
Hydrogen	0.60	1.91	6	-6	0.08	0.06
LNG	0.22	1.77	6	-5	0.22	0.11
Nuclear	-0.45	1.85	6	-6	0.34	0.24
HFO	-0.45	1.48	5	-5	0.13	0.28
Ammonia	-1.01	1.82	6	-6	0.06	0.62
Support for research						
Average	2.59	0.70	4.67	1.00	-0.28	0.07
Biofuel	2.21	0.92	5.00	1.00	0.59	0.19
Hydrogen	2.06	0.88	5.00	1.00	0.58	0.09
LNG	2.60	1.03	5.00	1.00	0.30	-0.34
Nuclear	2.78	1.21	5.00	1.00	0.25	-0.89
HFO	3.04	1.14	5.00	1.00	-0.06	-0.73
Ammonia	2.82	1.07	5.00	1.00	0.16	-0.47
Support for use						
Average	2.84	0.67	4.67	1.00	-0.56	0.61
Biofuel	2.48	0.92	5.00	1.00	0.14	-0.17
Hydrogen	2.37	0.88	5.00	1.00	0.10	-0.31
LNG	2.83	0.99	5.00	1.00	0.13	-0.10
Nuclear	3.00	1.17	5.00	1.00	-0.01	-0.69
HFO	3.24	1.06	5.00	1.00	-0.21	-0.35
Ammonia	3.12	0.99	5.00	1.00	-0.12	-0.01

Table 37: Tests for net associations variable

Univariate tests

		Test statistic	Test statistic value	P value	Bonferroni-corrected critical P value
Country	One Way Anova	F (.05, 3, 988)	1.358	0.254	0.01
Location	One Way Anova	F (.05, 7, 984)	1.066	0.383	0.01
Gender	One Way Anova	F (.05, 4, 987)	0.422	0.793	0.01
Age	Correlation	r	-0.107*	0.001	0.01

Multivariate tests

	F value	P value	Bonferroni-corrected critical P value
Country	2.581	0.052	0.005
Location	0.922	0.488	0.005
Gender	2.605	0.107	0.005
Age	0.510	0.475	0.005
Country × Age	1.705	0.164	0.005
Gender × Age	0.427	0.514	0.005
Location × Age	1.172	0.316	0.005
Country × Gender	0.342	0.795	0.005
Country × Location	1.305	0.171	0.005
Location × Gender	0.498	0.836	0.005

*indicates significance at the Bonferroni-corrected critical P value.

Table 38: Deviations between actual and expected associations

	Biofuel	Hydrogen	LNG	Nuclear	HFO	Ammonia
Reduces Emissions	1.3%	4.1%	-2.9%	4.1%	-6.2%	-3.2%
Safe	1.6%	-0.4%	2.8%	-2.7%	2.5%	-3.0%
Sustainable	4.9%	2.5%	-0.7%	-0.3%	-4.6%	-3.8%
Available Now	-2.7%	-3.9%	7.8%	-1.6%	9.7%	-5.7%
Shows Potential	4.3%	4.9%	-0.9%	-2.7%	-5.8%	-1.8%
Interesting	2.7%	4.1%	0.1%	-2.8%	-4.2%	-1.2%
Resource Intensive	2.6%	-1.4%	-0.1%	-3.6%	1.5%	1.8%
Negative By-products	-5.0%	-8.0%	2.4%	0.8%	11.8%	2.0%
Unproven	0.1%	0.0%	-2.0%	-2.0%	-2.6%	6.5%
Expensive	-0.8%	-0.4%	-1.0%	1.7%	0.4%	0.0%
Risky	-7.6%	-1.3%	-2.6%	7.3%	-1.6%	5.6%
Challenging	-1.4%	-0.1%	-3.0%	1.9%	-0.8%	2.9%

Table 39: Additional question analysis (%)

	Biofuel	Hydrogen	LNG	Nuclear	HFO	Ammonia	Avg.
Awareness of alternative fuels							
Have heard of [fuel] as an alternative shipping fuel	19	18	18	27	31	8	20
Have heard of [fuel], but not for shipping	52	55	44	46	17	15	38
Total	**71**	**73**	**62**	**73**	**48**	**22**	**58**
Have not heard of [fuel]	29	27	38	27	52	78	42
Could explain to someone else							
Agree	50	53	44	43	36	32	43
Neutral	36	33	39	36	40	42	38
Disagree	14	14	17	21	24	27	19
Support for research							
Agree	66	71	47	46	32	38	**50**
Neutral	26	24	35	25	33	37	**30**
Disagree	8	5	18	29	35	24	**20**
Support for use							
Agree	48	53	34	32	21	21	**35**
Neutral	41	40	46	37	40	48	**42**
Disagree	10	7	20	32	40	31	**23**
Net Associations	**21**	**20**	**10**	**-15**	**-20**	**-40**	**-3**

SUMMARY OF FINDINGS

5.0 Summary of findings

This chapter summarises the findings and implications of the three studies reported in this thesis, drawing on marketing theory and market research techniques to advance public engagement with emerging climate technologies. The main findings are summarised below in relation to individual research questions. The chapter then concludes by discussing the research contributions, implications, and potential avenues for further research.

5.1. Main findings

RQ1.1 To what extent to public perceptions of climate engineering differ between technologies?

Analysis of data from across all samples indicates the public remain largely uninformed and wary of climate engineering technologies (Chapter 2.0 and 3.0). In line with similar studies (Cummings et al., 2017), public awareness of climate engineering technologies remains low, with less than one fifth of participants reporting prior knowledge. Citizens mostly associated negative attributes with climate engineering: *Unknown effects, risky* and *artificial* account for over half of all attribute associations.

Carbon dioxide removal (CDR) technologies are preferred over solar radiation management (SRM), particularly for citizens with pro-ecological views. Public perceptions of bioenergy with carbon capture and storage (BECCS) and direct air capture and carbon storage (DACCS) are relatively positive, compared to stratospheric aerosol injection (SAI) and mirrors in space (MIS) that are mostly negative. Although perceptions of enhanced weathering (EW) and marine cloud brightening (MCB) are somewhat negative overall, analysis suggests that citizens found the two technologies relatively unremarkable.

Patterns of support for small scale trials closely resemble perception data. Over two fifths of citizens support BECCS, DACCS, and EW trials, approximately a third support MCB and MIS trials, and less than a quarter support SAI trials.

RQ1.2 To what extent do public perceptions of climate engineering differ between countries?

Analysis of data from NZ, Australia, UK, and USA found public perceptions were remarkably consistent between countries (Chapter 2.0). UK citizens are slightly less negative towards CDR approaches than US, AU, and NZ citizens. Similarly, UK and US citizens are also slightly less negative towards SRM approaches than AU and NZ citizens. Despite these small differences, our analyses indicate there are no substantial differences in climate engineering perceptions between the four countries.

RQ1.3 To what extent have public perceptions of climate engineering evolved between 2012 and 2018?

Comparisons of data from 2012 and 2018 in NZ and Australia found public perceptions of climate engineering remained stable (Chapter 2.0). New Zealanders' perceptions of EW, MCB, MIS, and SAI improved slightly over the six-year period, whereas Australians' perceptions remain unchanged. Despite the small differences in NZ, our analyses found no substantial changes in climate engineering perceptions over time.

RQ2.1 To what extent does encouraging intuitive or reflective thinking affect public perceptions of climate engineering?

Despite concerns that public engagement surveys elicit poorly considered responses; experimental evidence found encouraging additional thinking made no difference to participants' responses (Chapter 3.0). The data show participants in the Control and Intuitive treatment groups default to fast intuitive judgements about climate engineering. Despite successfully encouraging participants in the reflective treatment to spend more time considering their evaluations, the data show no differences in public perceptions between treatments. These analyses suggest encouraging reflective thinking is unlikely to override citizens intuitive snap-judgements about emerging technologies.

RQ2.2 To what extent do public perceptions of climate engineering differ between participants who choose to consider their responses for longer than those that respond quickly?

Participants that spent longer considering their responses also tended to have stronger opinions about climate engineering (Chapter 3.0). Though survey interventions to encourage reflective thinking did not affect participant responses, post hoc analysis found slight correlations between response time and stronger (more negative) perceptions. The findings suggest participants with stronger views may take more time to consider their response, without prompting. That is, they suggest stronger views may cause more thorough consideration, rather than thorough consideration causing stronger views.

RQ3.1 What are the UK public's perceptions of alternative shipping fuels?

UK public perceptions differ substantially between alternative shipping fuels (Chapter 4.0). Citizens strongly dislike ammonia, perceived as unproven, risky, and lacking availability. Despite the lingering stigma and perceived risk, nuclear is preferred over heavy fuel oil (HFO) due to concerns about negative by-products, emissions, and lacking potential. Nonetheless, perceptions of HFO and Nuclear are largely negative. In contrast, perceptions of liquid natural gas are somewhat positive, due to its perceived availability, suggesting it could provide an acceptable near-term option while other fuels are developed. Finally, perceptions of biofuels and hydrogen are mostly positive, owing to biofuel's perceived low risk and hydrogen's lack of negative by-products.

Support for research and use also differed substantially between fuels. Depending on the fuel in question, between 32% and 71% support further research and between 21% and 53% support their use. The analyses also found a "yes in my back yard" (YIMBY) effect, where citizens that live near ports are more supportive of alternative fuels.

5.2. Implications and contributions

5.2.1. Theoretical and methodological contributions

Overall, the research made several contributions, including both theoretical and methodological advancements. These advancements, discussed in the following subsections, contribute to literature on associative network theories of memory (ANTM), cognitive association methodologies, dual-process theories of human reasoning, survey methodologies, and mixed-methodologies for public engagement with emerging technologies.

ANTM and cognitive association methodologies.

This research provided additional validation for the application of *associative network theories of memory* (Anderson, 1983; Anderson & Bower, 1973) and cognitive associations methodologies (Romaniuk, 2013; Wright et al., 2014) for public engagement with emerging technologies. The research elicited measures that remained stable between countries (Chapter 2.0), over time (Chapter 2.0), at varying levels of cognitive effort (Chapter 3.0), across multiple categories of emerging technologies (Chapter 2.0 and 4.0), and between qualitative and quantitative techniques (Chapter 4.0). Additionally, this research confirmed that modelling cognitive associations with emerging technologies – based on ANTM – elicited valuable insights into public perceptions of emerging technologies, discussed in Section 5.1.

The application of ANTM and modelling of cognitive associations was further validated by observed consistencies between the research data and broader theory from the risk literature. Specifically, Slovic and Peters (2006) observe that people judge risky activities based on how they feel about them. If their feelings are positive, they perceive high benefits and low risk, and vice versa if their feelings are negative. Similar patterns were observed in the concept maps (Figures 2, 7-10, 24) where participants tended to associate more positive attributes and less negative attributes with the technologies they liked, and vice versa with the technologies they disliked.

Overall, the consistency of these findings, across several studies and with theory from risk literature (discussed above), represents a major contribution by advancing the application of ANTM and cognitive association methodologies in the public engagement discipline.

Dual processing theories and survey methodologies

In addition to ANTM, this research also introduced *dual processing theories* of human reasoning into the public engagement discipline, yielding both theoretical and methodological implications.

The experimental evidence indicates that people typically rely on intuitive (Type 1) information processing, rather than reflective (Type 2) information processing to form their opinions about unfamiliar emerging technologies (Chapter 3.0). Moreover, the research found that encouraging people to engage in reflective (Type 2) information processing made no difference to their intuitive reactions. These findings align with dual processing theories that suggest Type 1 processes are the default form of human reasoning. When confronted with a task, Type 1 processes generate fast, automatic responses whereas Type 2 processes may (or may not) intervene to either endorse or override the initial response (Evans, 2007; Evans & Stanovich, 2013; Kahneman & Frederick, 2002).

The findings also align with similar theories already applied in the emerging technologies literature. Specifically, the low-information rationality model (Popkin, 1994; Scheufele, 2006) that states people are unlikely to process masses of information to draw thoroughly reasoned conclusions. Instead, most are cognitive misers that form opinions toward emerging technologies based on limited information.

These findings also contradict the discredited knowledge deficit model of science communication that implies citizens should acquire as much information as possible to form their opinions about emerging technologies (Scheufele, 2006). This model assumed that opposition toward emerging technologies could be addressed by educating the public, though empirical evidence fails to prove a direct connection between knowledge and support (Corner & Pidgeon, 2010). The findings that people rely on intuitive snap judgements that remain unaffected by more reflective consideration

(Chapter 3.0) further discredits the knowledge deficit model, suggesting more knowledge is unlikely to change public opinion toward emerging technologies.

These theoretical advances have methodological implications for public engagement surveys. Despite criticism of the rapid responses elicited by public engagement surveys, the research concludes that self-administered surveys remain a useful tool for large-scale public engagement – without the need for manipulations to increase participants cognitive effort. The main methodological implication is that participants, and indeed the wider public, form intuitive judgements of emerging technologies by default. Thus, contrary to researchers concerns, there is evidence to support the external validity of survey mechanisms for public engagement.

Mixed methodologies for public engagement

The final methodological contribution of this thesis is to demonstrate the value of a mixed-method approach to modelling cognitive associations. While the concept of mixed-method approaches are not particularly novel within public engagement research (e.g., Bellamy et al., 2019), the third publication (Chapter 4.0) is the first known application of a mixed-method approach to modelling cognitive associations.

Overall, the additional qualitative analysis provided valuable insights into the driving factors and nuances behind participants' perceptions of emerging technologies. For example, direct quotes from the initial qualitative interviews were particularly useful for cross-validating participants perceptions and explaining why certain attributes were (or were not) associated with the different technologies. That is, the mixed-method approach was better at explaining why participants perceived each technology the way they did.

5.2.2. Implications for public engagement research

The theoretical and methodological advances discussed above have several implications for public engagement researchers and practitioners. In particular, the validation of cognitive association methodologies opens several avenues for ongoing and expanded use of the methodology by public engagement researchers, discussed below:

First, the findings demonstrated the usefulness of cognitive association techniques, and survey mechanisms in general, for rapidly conducting large-scale, cross-country public engagement research. A rapid cross-country approach is particularly important with the urgent need for emerging climate technologies that will – for better or worse – have global impacts on society and nature.

Second, the first publication (Chapter 2.0) also demonstrated the usefulness of cognitive association methodologies for benchmarking and tracking public perceptions over time. With many emerging climate technologies still in their infancy, the ability to gather ongoing public feedback is vital for ensuring technological development aligns with societal expectations.

Third, the second publication (Chapter 3.0) demonstrated that, contrary to public engagement researchers concerns, participants in public engagement research need not engage in thorough consideration prior to forming their opinion. Instead, dual process theory, the low-information rationality model, and this thesis' findings, all suggest that participants typically form their opinions based on intuitive snap judgements. Thus, the research finds no threat to the external validity of survey mechanisms as they appear to rely on the same fast, intuitive information processing used by the broader public to form opinions on emerging technologies.

Finally, the third publication (Chapter 4.0) demonstrates the value of mixed method approaches to public engagement, particularly in exploratory studies where public perceptions are unknown. In addition to producing quantified and generalisable results, the mixed-method approach also explored the rationale and nuances behind public perceptions of emerging shipping fuels, despite no previous research published on the topic. The third publication also provides all the necessary information for other public engagement researchers to replicate the mixed-method approach in these, and other research domains.

Overall, the methods detailed in this thesis provide critical and valuable information for scientists, policymakers, and industry. As technologies continue to emerge in response to the worsening climate crisis, the techniques detailed in this thesis will make a valuable addition to the selection of public engagement methodologies.

5.2.3. Implications for scientists, policymakers, and industry

The research in this thesis also demonstrates that scientists, policymakers, and industry need to consider how emerging technological development aligns with public opinion. By engaging public early, scientists and industry can co-create publicly acceptable R&D trajectories for emerging climate technologies and policymakers can pre-empt public concern to ensure appropriate policies are in place.

Despite low awareness, citizens are perfectly capable of evaluating emerging technologies – even with limited time and information. These opinions are strong at times and vary substantially between technologies but are also stable across countries and over time.

Already CDR and SRM technologies have been met with public opposition. The first publication (Chapter 2.0) warned that the planned SCoPEx project – aiming to better understand stratospheric aerosol injection – may encounter substantial backlash, due to overwhelmingly negative public perceptions. Indeed, since its publication (Carlisle et al., 2020), the first test flight for SCoPEx in Sweden was cancelled, due to strong opposition from environmentalists and indigenous Sami communities ("Give research into solar geoengineering a chance," 2021). In response to the backlash, Harvard Professor David Keith, who is involved with the SCoPEx project reportedly claimed that surveys in other countries had shown support for climate engineering research and that "each time there has been real consultative process, all of those have suggested that public support for experiments like this is significant" (Fountain & Flavelle, 2021, para. 12). Despite the scientists' surprise, the research published from this thesis clearly found strong cross-country public opposition – 24% supported small scale trials and 41% opposed. The SCoPEx cancellation highlights the value of this research in informing scientists' understanding of public perceptions and adjusting their research activities appropriately.

As CDR, SRM and alternative fuels are developed, industry and policymakers will also find value in public engagement, the former for deciding where to invest their resources and the latter for designing appropriate policies prior to large-scale implementation.

5.3. Limitations and Future research

In addition to the advances made in this thesis, several opportunities exist to expand the research further and address any limitations.

An obvious starting point is expanding the scope of the public engagement, including new and (importantly) underrepresented countries, replicating in different cultures and languages, considering different technologies, or continuing to monitor changes in perceptions over time. One limitation of the current research is that all samples were drawn from developed, western countries. Since poorer and more vulnerable populations are likely to be worst affected by climate change (IPCC, 2022), calls are growing for public engagement efforts to expand into the Global South (Burns et al., 2016). Additionally, non-western and indigenous populations may present cultural differences that affect the generalisability of the research method and results, thus future research should replicate the methodologies across a broader spectrum of cultures to establish the cross-cultural validity of the method.

Public engagement research can also be influenced by the researchers' framing choices. These include the inclusion or exclusion of technologies under evaluation, the information provided to participants, and questionnaire design, both in terms of the questions asked and the possible responses a participant can give. Section 2.1.2 discusses the control of these framing effects in detail. Additionally, there are many well-known limitations and biases that emerge from the chosen methodologies, such as panel representativeness, internet coverage, survey fatigue (for professional panellists), speeding and flatlining, acquiescence bias, mid-point bias, and participant ambivalence toward the topic. Efforts to mitigate these limitations and biases are described in the method and supplemental sections of each study.

As identified in the second study (Chapter 3.0) another avenue for further research is to explore the role of intuitive and reflective thinking in deliberative methods of public engagement. Deliberative exercises, such as workshops or focus groups, encourage citizens to deliberate on emerging technologies over an extended period. Compared to traditional survey questionnaires, deliberative methods encourage participants to consider and discuss issues in a more thorough manner. What remains unclear is whether this additional deliberation influences citizens' perceptions (Abelson et al., 2003), and if so, whether it is the result of deeper consideration, or influence from other participants. A similar experimental approach, like the one used in the second study, could resolve these unanswered questions.

Finally, future studies could consider further opportunities for inter-disciplinary innovations where the marketing discipline can advance public engagement with science. This thesis drew on only a few market research techniques, including qualitative techniques used for brand attribute elicitation and a quantitative technique for modelling brands associative networks and mental market share. As identified earlier, marketing as a discipline has extensive expertise in evaluating new concepts, tracking perceptions, and communicating with the public. There is almost certainly more that can be gained by interdisciplinary applications of marketing theory and market research techniques.

6.0 References

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7.0 Appendices

7.1. Background: Climate change

Human-induced climate change is accelerating at an alarming rate (IPCC, 2022). Compared to a pre-industrial baseline, global temperatures have already increased by 1.09°C and will continue to rise until at least mid-century (IPCC, 2021). Scientific evidence unequivocally links these rising temperatures to increased greenhouse gas emissions from human activities (IPCC, 2021; Royal Society & US NAS, 2014). Scientists warn that continued greenhouse gas emissions will cause further warming and irreparable damage to the climate system (IPCC, 2018).

Acknowledging the impending climate crisis, a majority of nations adopted the Paris Agreement to limit global warming to well below 2°C (preferably less than 1.5°C) and avoid some of the worst impacts of climate change (UNFCCC, 2015). To meet these targets, individual nations declared various climate pledges to reduce their greenhouse gas emissions. According to the latest *Emissions Gap Report*, these pledges are insufficient, accounting for only 7.5% of the 30% to 55% reductions needed to stay on the least-cost pathway for 2°C and 1.5°C (respectively). Even if every nation met their current climate pledges, global temperature increases are likely to reach 2.7°C by 2100 (UNEP, 2021), posing severe risks for ecosystems and humanity (IPCC, 2022). With time running out, experts warn that ambitious action is urgently needed (UNEP, 2021).

Fortunately, emerging climate technologies (see following section) show promise for bridging the gap between current emissions and the reductions required to meet the Paris Agreement targets. However, with many of these technologies still under development and relatively unknown, it is unclear how the public will react, or whether public opposition may hinder their deployment. Early public engagement is therefore critical to identify acceptable decarbonisation pathways, guide research trajectories, and inform climate policy (Carr, Yung, & Preston, 2014). Herein lies the core focus of this thesis: Public engagement with emerging climate technologies.

7.2. Climate change responses and emerging technologies

Heyward (2013) provides a typology of potential responses to climate change, spanning from addressing the source of the issue – greenhouse gas emissions – through to addressing the outcomes of the issue – harm caused by rising temperatures. Table 40 reproduces this typology, edited for conciseness. The studies in this thesis are concerned with the technologies that fall under the first three preventative categories: *Mitigation*, *carbon dioxide removal* (CDR), and *solar radiation management* (SRM).

Table 40: A typology of responses to climate change (Heyward, 2013)

Strategy	Mitigation	CDR	SRM	Adaptation	Rectification
Aim	Minimise GHG emissions	Minimise atmospheric GHG volume	Minimise temperature increases.	Minimise impacts of temperature increases.	Providing redress for harm.

7.2.1. Mitigation (via alternative shipping fuels)

Mitigation of greenhouse gas emissions remains the core priority for achieving long-term decarbonisation goals. Fossil fuel consumption currently accounts for the majority of anthropogenic greenhouse gas emissions (IPCC, 2011, 2014). Accordingly, substantial mitigation efforts have focused on phasing out fossil fuels and transitioning towards renewable alternatives (Heyward, 2013; IPCC, 2011). Deployment of renewable energy technologies continues to increase rapidly (IPCC, 2011), such as wind and solar energy production, or electric vehicles. Yet, the implementation of renewable fuels in heavy industries, such as shipping, lag substantially behind. The shipping sector is a critical industry, accounting for 80-90% of world trade (Balcombe et al., 2019; T. W. P. Smith et al., 2014), but is also responsible for 2-3% of global greenhouse gas emissions (Faber et al., 2021; T. W. P. Smith et al., 2014). Alternative low-carbon fuels, such as hydrogen or ammonia, could drive substantial emission reductions for the sector (Balcombe et al., 2019) and contribute to the Paris

Agreement targets. Since these alternative fuels are in early stages of development, they provide an ideal context for testing public perceptions.

Table 41: Alternative shipping fuel descriptions

Shipping Fuels	**Brief Description**
Heavy Fuel Oil (HFO)	A common fossil fuel used in international shipping made from unrefined oil as a by-product of fossil fuel production. Using HFO will continue to emit greenhouse gases and other pollutants (McKinlay et al., 2020).
Liquid Natural Gas (LNG)	A fossil fuel-based alternative to HFO, used by some ships. LNG will continue to emit greenhouse gases and other pollutants but is generally cleaner than HFO (Balcombe et al., 2019; McKinlay et al., 2020).
Hydrogen	A non-toxic, but highly flammable gas that produces no greenhouse gas emissions at the point of use. Current manufacturing processes produce a lot of emissions, however, if enough renewable energy were available, new methods could produce hydrogen without any emissions (Balcombe et al., 2019; Bicer & Dincer, 2018; McKinlay et al., 2020).
Ammonia	A toxic and corrosive chemical that produces no greenhouse gas emissions at the point of use, but may release nitrogen-based pollutants (Bicer & Dincer, 2018; McKinlay et al., 2020)
Biofuels	Biofuels are made from plants that absorb carbon dioxide as they grow. When ships use biofuels, carbon is released back into the atmosphere. If the production of biofuels utilized renewable energy sources, then biofuels could have a neutral emission profile (Kesieme et al., 2019; Royal Society, 2008)
Nuclear	Nuclear fuel uses radioactive materials to generate energy. Nuclear fuel could be made without any greenhouse gas emissions as long as the materials are mined and refined using renewable sources (Balcombe et al., 2019).

Study three (Chapter 4.0) investigates public perceptions of the six alternative shipping fuels described in Table 41 above. The above list is not an exhaustive list of alternative shipping fuels. The six fuels were selected based on a combination of factors, including expert opinion; scientific assessment; current usage; and industry, academic, and policy interest.

7.2.2. Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM)

While mitigation is important for reducing future emissions, the issue of historical greenhouse gas emissions remain (Heyward, 2013). Thus, a second class of *carbon dioxide removal* (CDR) or *negative emissions technologies* (NET's) have emerged that aim to draw already emitted greenhouse gases from the atmosphere (Minx et al., 2018; Royal Society & Royal Academy of Engineering, 2018; US NAS, 2015a). Already, implementation of CDR technologies is assumed in IPCC scenarios to limit global warming to 1.5°C or reduce global temperatures in the case of an overshoot (IPCC, 2018).

Finally, a controversial class of technologies known as *solar radiation management* (SRM), or *radiative forcing geoengineering* are considered as a third approach to cool the planet. SRM aims to artificially cool the planet by reflecting a portion of sunlight away from the earth (Lawrence et al., 2018; MacMartin et al., 2018; US NAS, 2015b). While SRM could cool the planet and avoid the worst impacts of global warming, it does nothing to address the underlying issue of greenhouse gas emissions (Royal Society, 2009) and substantial risks and uncertainties remain (IPCC, 2018, 2022). Thus, mitigation and CDR approaches are generally considered preferable alternatives to SRM.

In the past CDR and SRM have been lumped together under the term *climate engineering* or *geoengineering* defined by the Royal Society as "deliberate large-scale intervention in the Earth's climate system" (Royal Society, 2009, p. ix). However, this taxonomy has fallen out of fashion due to concerns that SRM's higher risk profile might negatively affect perceptions of CDR approaches (Colvin et al., 2019; Horton, 2015). Thus, this thesis disaggregates CDR and SRM where possible. Publication One and Two (Chapter 2.0 and 3.0) include three CDR and three SRM techniques detailed in Table 42 below. The below list is not an exhaustive list of CDR and SRM technologies. The six technologies were selected based on a combination of factors, including expert opinion; scientific assessment; comparability with previous studies; and industry, academic, and policy interest.

Table 42: Summary of common CDR proposals

CDR proposals	Brief description
Bioenergy with Carbon Capture and Storage (BECCS)	Biomass is harvested and combusted to generate energy. The resulting CO_2 emissions are captured and sequestered using carbon capture and storage methods, typically underground (Kemper, 2015; Royal Society & Royal Academy of Engineering, 2018).
Direct Air Capture and Carbon Storage (DACCS)	CO_2 is captured from ambient air using engineered structures. Concentrated CO_2 is produced and sequestered, typically underground (Lackner, 2014; Royal Society & Royal Academy of Engineering, 2018).
Enhanced Weathering (EW)	Atmospheric CO_2 is naturally sequestered via the weathering of specific minerals over time. The weathering process is accelerated by grinding and spreading the minerals over land or ocean (Hartmann et al., 2013; Royal Society & Royal Academy of Engineering, 2018; US NAS, 2015a).

SRM proposals	Brief description
Marine Cloud Brightening (MCB)	Spraying sub-micron sea water droplets to increase cloud albedo and reflect incoming solar radiation to cool the earth (Lawrence et al., 2018; Salter et al., 2014).
Mirrors in Space (MIS)	Scattering incoming solar radiation using reflective materials or structures placed in Earth's orbit (Angel, 2006; McInnes, 2010; Salazar, McInnes, & Winter, 2016).
Stratospheric Aerosol Injection (SAI)	Injecting reflective particles (e.g., sulphates) into the stratosphere to reflect incoming solar radiation and cool the earth (Crutzen, 2006; Lawrence et al., 2018; Robock, 2014).