LETTERS
PUBLISHED ONLINE: 12 JANUARY 2014 | DOI: 10.1038/NCLIMATE2087
nature climate change

A quantitative evaluation of the public response to climate engineering

Malcolm J. Wright[1,2]*, Damon A. H. Teagle[3] and Pamela M. Feetham[4]

Atmospheric greenhouse gas concentrations continue to increase, with CO_2 passing 400 parts per million in May 2013. To avoid severe climate change and the attendant economic and social dislocation, existing energy efficiency and emissions control initiatives may need support from some form of climate engineering. As climate engineering will be controversial, there is a pressing need to inform the public and understand their concerns before policy decisions are taken. So far, engagement has been exploratory, small-scale or technique-specific. We depart from past research to draw on the associative methods used by corporations to evaluate brands. A systematic, quantitative and comparative approach for evaluating public reaction to climate engineering is developed. Its application reveals that the overall public evaluation of climate engineering is negative. Where there are positive associations they favour carbon dioxide removal (CDR) over solar radiation management (SRM) techniques. Therefore, as SRM techniques become more widely known they are more likely to elicit negative reactions. Two climate engineering techniques, enhanced weathering and cloud brightening, have indistinct concept images and so are less likely to draw public attention than other CDR or SRM techniques.

The United Nations has sought carbon dioxide emissions controls to address the risks of climate change through the Kyoto Protocol and the Copenhagen Diagnosis. The Intergovernmental Panel on Climate Change warns that if average global surface temperatures rise more than 2 °C above pre-industrial levels, the effects on the Earth's eco-systems and species will be extensive[1]. Average global surface temperatures have risen around 0.74 °C in the past one hundred years and a further rise of 0.6 °C is believed inevitable[2]. Unless CO_2 emissions are reduced by 50% before 2050, average global surface warming will exceed 2 °C this century[3]. Present methods of mitigation and adaptation seem inadequate, as growth in atmospheric carbon dioxide continues unchecked[4–7].

The failure of existing mitigation methods has led to investigation of alternative solutions including climate engineering, defined as deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change[4]. CDR technologies seek to reduce atmospheric carbon dioxide concentration and include: afforestation; biochar; enhanced weathering; ocean fertilization; ocean liming; and various forms of air capture. SRM technologies seek to reduce temperatures by using reflective technologies to alter the balance of solar radiation and include: cloud brightening; stratospheric aerosols; roof whitening; and mirrors in space[5,8]. To assist the policymaking process regarding geoengineering, climate experts and public opinion experts must work together to understand likely public reaction to these technologies[2,9].

Initial qualitative work to engage the public on climate engineering has taken place in the United Kingdom and included small group discussions, open access events and a qualitative online survey of stakeholders[10,11]. These showed low awareness of climate engineering, but a preference for CDR over SRM on the basis that CDR techniques mitigate increasing atmospheric CO_2, the root cause of anthropogenic climate change. This small-sample qualitative approach was further applied to stratospheric aerosols, identifying considerable public discomfort with this particular technique[12,13].

Large-scale quantitative work remains at an exploratory stage. One study examined public perceptions of SRM and the characteristics of those who were more, or less, opposed in North America and the United Kingdom, but did not compare specific SRM or CDR techniques[14]. Another US-based study used a split sample to compare two relatively safe ($n = 506$) and two less safe ($n = 500$) climate engineering techniques. However, the concept presentations were not adequately controlled, and a large bias eventuated between the subsamples[15]. A third study ($n = 1{,}822$) used one-sentence descriptions of CDR and SRM to gauge relative support in the United Kingdom, but did not investigate any technique in detail[16].

Here we report large-scale quantitative work that systematically examines and compares public reaction to six climate engineering techniques in a controlled fashion. We draw on techniques from Marketing, a discipline with extensive experience in public engagement and evaluation of concepts. Brand researchers are lead users of the psychological techniques used to elicit cognitive associations, and have deployed these in large-scale surveys to evaluate brand image for over 20 years[17–19]. These approaches are based on Human Associative Memory theory[20] and the Adaptive Control of Thought model[21] as these describe the encoding, storage and retrieval of information in memory, and explain how an external stimulus causes cascading activation through a network of associated nodes (the basic unit of semantic memory). When an external stimulus brings a concept to mind, these associated memory nodes are likely to be retrieved into working memory to assist problem solving. Brand researchers have developed these theories into a systematic and quantitative approach to eliciting cognitive associations for brands. These developments can also be adapted to concepts in other domains, such as evaluation of climate engineering techniques. This provides a method of understanding public reaction to scientific, as well as commercial, concepts, in that it identifies the memory structures likely to be evoked by

[1]Massey University, Tennent Drive, Palmerston North 4410, New Zealand, [2]Ehrenberg-Bass Institute for Marketing Science, University of South Australia, North Terrace, Adelaide, South Australia 5000, Australia, [3]Ocean & Earth Science, National Oceanography Centre Southampton, University of Southampton, European Way, Southampton SO14 3ZH, UK, [4]School of Communication, Journalism and Marketing, Massey University, Tennent Drive, Palmerston North 4410, New Zealand. *e-mail: Malcolm.Wright@marketingscience.info

discussion of the concepts. We therefore apply recent advances in these techniques[19] to climate engineering, assisted by standard techniques for the presentation and evaluation of new concepts[22].

In doing so, we find it helpful to distinguish between deliberative, persuasive and descriptive public engagement with science. Deliberative engagement provides opportunities to build a shared understanding of the local, cultural and social factors that affect engagement with science[23]. Persuasive engagement may effect behavioural change, but can be contested if its objectives do not have broad scientific or community support[24]. Our approach is Descriptive, and instead seeks to provide inputs for policy decisions, offering controlled comparisons between techniques and a method for tracking changes in public perceptions over time.

Although this represents a departure from existing work on public engagement with science, it seeks to extend rather than supplant such research. Existing qualitative and ethnographic approaches are well suited to engaging with Deliberative or reflective thinking. Our Descriptive approach extends the measurement of public engagement to the associative or intuitive thinking that dominates much of everyday cognition. To quote Daniel Kahneman: associative thinking is 'more influential than your experience tells you, and it is the secret author of many of the choices and judgments you make'[25]. Unless both types of thinking are considered, the measurement of public engagement with geoengineering will be incomplete.

The brand association metrics we use are identical to those applied commercially[19] with two minor exceptions. First, owing to the nature of the research, attribute associations are prompted by the climate engineering techniques, whereas in commercial research they are usually prompted by the product category. Previous research shows that such alternative elicitation methods deliver virtually indistinguishable results, with commercial approaches simply adopting the method that yields the most efficient data collection[26]. Second, we construct and evaluate an overall net positive measure specifically for this research, in contrast to brand research that concentrates on positive rather than negative associations[27].

We proceed through qualitative ($n = 30$) and quantitative ($n = 2{,}028$) phases. The qualitative phase uses in-depth interviews to reveal attributes that represent the memory nodes most relevant to climate engineering. We first identify a wide range of attributes, and then truncate these to 12 representative attributes for quantitative data collection. Following data collection and diagnostic tests in the quantitative phase[19] we reduce the attributes analysed to 10.

The quantitative data are gathered using a commercial provider of online surveys in Australia ($n = 1{,}006$) and New Zealand ($n = 1{,}022$). Six climate engineering concepts are tested: Biochar (making charcoal from vegetation to lock in CO_2); Enhanced Weathering (increasing the rate that carbon dioxide dissolves silicate minerals to form limestone); Air Capture (building structures that filter CO_2 from the air); Stratospheric Aerosols (spreading very small particles in the upper atmosphere to reflect sunlight); Cloud Brightening (automated ships spraying small seawater droplets over the ocean to reflect sunlight); and Mirrors in Space (placing large mirrors or sunshade structures in orbit to block or reflect sunlight). Participants viewed an on-screen visual of each climate engineering technique and read a brief definition of the concept inclusive of advantages and disadvantages.

The primary outcome measures are the count of attribute associations elicited from individual participants for each technique, analysed in line with brand image analysis methodology[19]. We report quantitative results by country to avoid aggregation bias and to provide built-in replication as a robustness check.

The results show substantial variation in attribute popularity, measured as each attribute's share of all associations (Table 1). The variation in attribute popularity has a correlation between countries of $r = 0.99$.

Table 1 | Attribute association rankings.

Ranking	Attribute	Australia: Share of all associations (%)	New Zealand: Share of all associations (%)
1	Unknown effects	24	25
2	Risky	16	16
3	Artificial	12	13
4	Quick-fix	8	7
5	Eyesore	8	9
6	Understandable	7	8
7	Controllable	7	7
8	Environmentally friendly	7	6
9	Long-term sustainability	6	6
10	Cost-effective	5	3

Of the 10 attributes analysed, the most frequently chosen are the five negative attributes, and the least frequently chosen are the five positive attributes. Over two-thirds of all associations are made to negative attributes. Two attributes—unknown effects and risky—account for around 40% of associations.

When the same data are aggregated by climate engineering concept, public support for techniques can be ranked by subtracting negative associations from positive associations to provide a 'net positive' association metric (Table 2) that is approximately normally distributed (Supplementary Figs 1–4). Univariate and multivariate tests show that net positive scores do not vary with respondent characteristics, except for a slight tendency to increase with age (Supplementary Tables 3 and 4). For both countries, the highest net positive association rates are for CDR techniques and the lowest are for SRM techniques. The correlation between Australia and New Zealand data is again $r = 0.99$.

This high inter-study reliability is familiar to brand image researchers as attribute popularity and brand image rankings are typically very stable[19]. In addition, here as in other brand image studies, there is structure in the data (Supplementary Table 6). The individual attribute scores vary with the overall popularity of the attribute and with the association rate for the particular concept. Interpretation requires a chi-square calculation of expected cell counts. Concept image is then reported as a chart of the percentage point skews (deviations) from these expected values (Supplementary Table 7) to show the distinctive image for each concept.

This practice is illustrated with diametrically opposed concept images for Biochar and Mirrors in Space in New Zealand (Fig. 1). Here the order of attribute presentation is the inverse of popularity, placing the positive attributes at the top. Biochar skews towards the positive attributes (such as environmentally friendly and long-term sustainability) and away from the negative attributes, whereas Mirrors in Space skews away from the positive attributes and towards most of the negative attributes (particularly risky and unknown effects).

In subsequent surveys concept maps may change. If the x axis skews alter, then the concept image has changed. For example, Biochar may skew less towards environmentally friendly and more towards artificial. If y-axis order changes, the relative popularity of the attributes, or the relative accessibility of each memory node, will have changed. It might be, for example, that for all concepts participants become less likely to mention risky and more likely to mention controllable. Repeated surveys will show how concept image and category knowledge evolve over time.

Table 2 | Memory associations for climate engineering techniques.

	Biochar	Air capture	Enhanced weathering	Cloud brightening	Stratospheric aerosols	Mirrors in space	Total
Australia							
*n**	672	674	666	672	666	674	1,006
Count of associations	1,600	1,885	1,581	1,706	1,789	1,594	10,155
Positive associations	48%	43%	37%	26%	23%	20%	33%
Negative associations	52%	57%	63%	74%	77%	80%	67%
Net positive associations	−4%	−13%	−26%	−49%	−54%	−59%	−34%
New Zealand							
*n**	670	691	683	670	683	691	1022
Count of associations	1,774	2,130	1,708	1,860	1,917	1,800	11,188
Positive associations	52%	42%	34%	22%	15%	14%	30%
Negative associations	48%	58%	66%	78%	85%	86%	70%
Net positive associations	3%	−16%	−32%	−57%	−70%	−73%	−40%

X^2 tests for independence show significant differences for both countries (Supplementary Table 6). For the positive and negative associations reported in here, the standard errors of the proportions range from 0.008 to 0.012 (or 0.08%–1.2%). The *z*-values for the differences between adjacent techniques range from −3.7 to −25.4. Therefore, all differences in this table are statistically significant. *To minimize fatigue, each participant evaluated only four concepts.

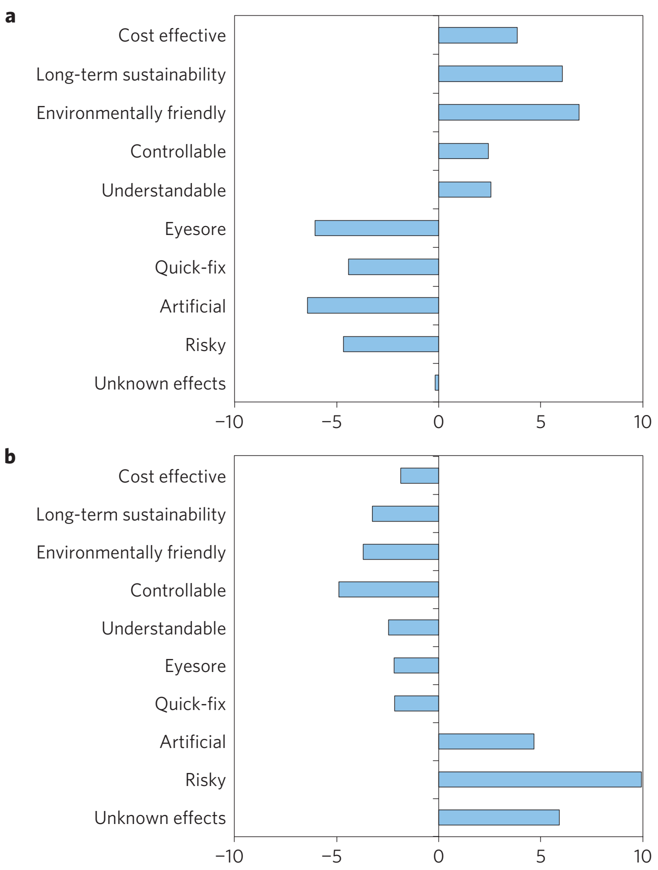

Figure 1 | Sample concept maps for New Zealand. a, Biochar concept image. **b**, Mirrors in space concept image. Percentage point deviations from expected attribute counts.

There are 12 concept images in the present research. These are presented below in an abbreviated format (Fig. 2) that maintains the order of attributes used in the illustrative concept maps (Fig. 1).

The concept images are similar for Australia and New Zealand, but vary between techniques. Biochar and Air Capture have the most positive concept images, although Air Capture also skews heavily towards eyesore (the sixth attribute). Stratospheric Aerosols and Mirrors in Space have the most negative concept images, generally skewing away from positive attributes and towards negative attributes. Taken together, the results show that public evaluation of climate engineering is negative. Where there are positive associations, they heavily favour CDR techniques over SRM. One implication is that as SRM techniques become more widely known, they are more likely than CDR techniques to elicit negative public reactions.

A further point is that techniques vary considerably in distinctiveness: Biochar and Air Capture have distinctive and positive concept images; Stratospheric Aerosols and Mirrors in Space have distinctive and negative concept images; Enhanced Weathering and Cloud Brightening are not very distinctive (their skews are small). Branding theory predicts that more attention will be directed at distinctive stimuli[28]. Therefore, public reaction to Enhanced Weathering and Cloud Brightening may be comparatively muted.

The attribute list indicates the language people recognize as well as the associations they hold. Memory theory indicates that people process familiar stimuli more easily, and that each time a concept or related association is activated, the chances of future activation are increased[20,21]. It also suggests that the chances of processing will be reduced if competing concepts are also present in working memory[20]. Although our primary objective is Descriptive engagement, these findings may provide guidelines for effective communication in Deliberative or Persuasive settings. Communication will be more effective if the specific positive and negative terms elicited in this research are used to construct messages, and if interference from competing concepts is minimized. This will facilitate activation of the relevant concept nodes, making public interaction with climate engineering proposals more likely.

These results quantify public perceptions of climate engineering, provide controlled comparisons of techniques to inform policy, and identify language to be used for effective public communication. The process is systematic and the outputs are both quantitative and comparative. However, the results of this study reflect a particular set of information at a particular point in time. The results will probably change as the public dialogue unfolds, as the public are exposed to other climate engineering concepts and provided with additional scientific information on the techniques presented here. Re-applying the present methods provides a solution to the problem of assessing the exposure impact of scientific information in a real-world setting[29]. That is, it provides a method of tracking changes in public perceptions if climate engineering moves from conceptual discussion to possible implementation.

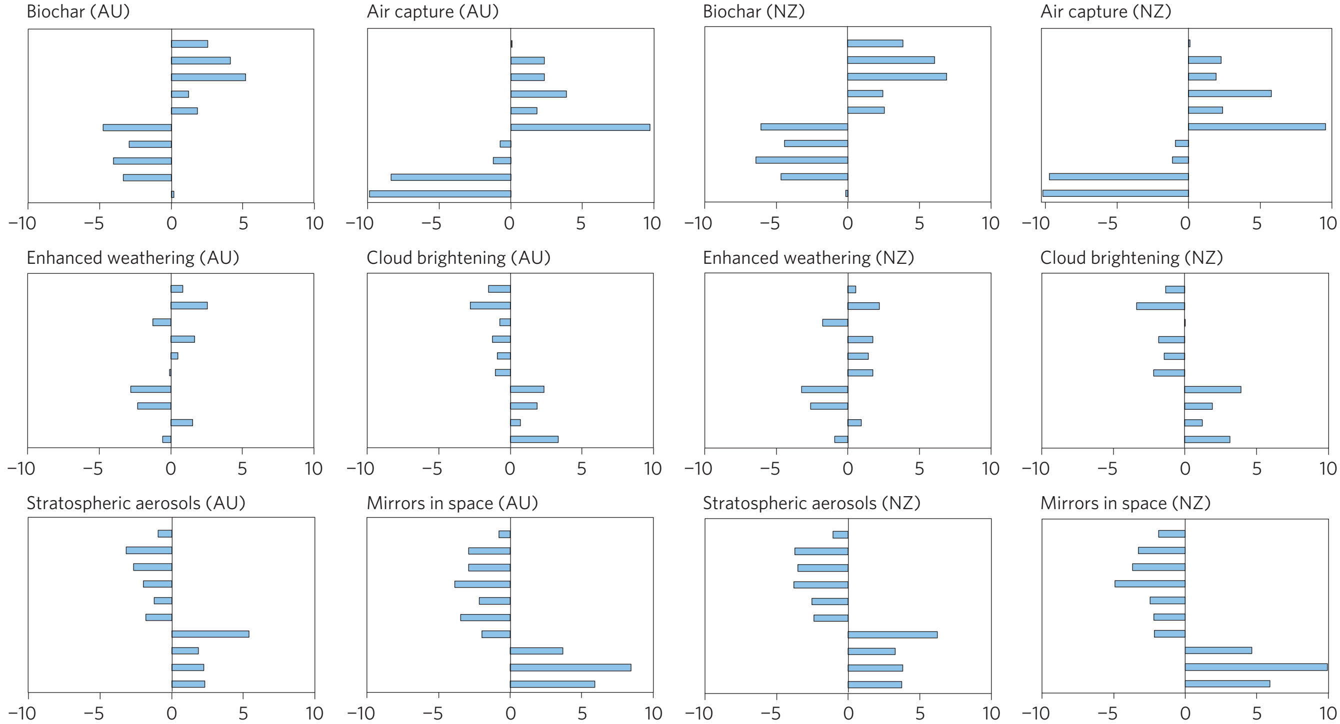

Figure 2 | Summary of all concept maps. Percentage point deviations from expected attribute counts. The order of attributes used in the concepts maps is the same as in Fig. 1. AU, Australia; NZ, New Zealand.

Methods

The qualitative phase used in-depth interviews to examine Biochar, Air Capture, Cloud Brightening, and Stratospheric Aerosols. Participants viewed concept boards similar to those developed for the Experiment Earth deliberative workshops[10] but also including later work in this area[8,30]. Concept boards were presented to a convenience sample of 30 New Zealanders purposely selected to maximize demographic diversity. The sample varies from 18 to 77 years in age, with 47% male and 53% female, and qualifications ranging from none to postgraduate degree (Supplementary Table 1). Fifteen participants described their impressions by selecting from lists of pre-determined attributes. The other 15 were interviewed using Kelly's Repertory Grid, a method for evoking attributes from comparisons of similarities and differences between concepts. The terminology elicited from Kelly's Repertory Grid, along with language common across both methods, was adopted in the quantitative phase of the research. Some similar-seeming attributes were selected for the quantitative phase (unknown effects, unpredictable and risky) to reflect various uncertainties about collateral effects, impact on global warming and difficulty in reversing the intervention.

For the quantitative phase, Enhanced Weathering and Mirrors in Space were added to the concepts examined. This maintained a balance between CDR and SRM techniques, and included the six techniques judged by the authors to be of most interest in present scientific debates. A commercial online panel provider (ResearchNow, http://www.researchnow.com) was engaged to recruit participants. To avoid response bias, participation invitations referred to social research rather than climate engineering specifically. The provider issues invitations to panel members continuously, achieving demographic quotas by monitoring responses and issuing additional invitations to under-represented groups. Demographic representation in the sample is widespread and appropriately balanced for age, gender, education and location (Supplementary Table 2). There are some small demographic differences between the sample and census data, but few significant differences on the net positive variable between demographic groups. There may be some recruitment bias from panel formation; however, this is unlikey to be substantial owing to the size of the panels ($n = 75{,}000$ in New Zealand, and $n = 189{,}000$ in Australia). Coverage bias is minimized with Australia and New Zealand having over 80% of the population as Internet users. Fieldwork included both weekdays and weekends.

Other measures taken to minimize framing effects and bias included: to activate relevant memory networks, participants were initially asked negatively phrased questions about global warming (this was intended to force participants to parse the sentences, ensuring they were fully considered in working memory) and then given a brief explanation of the possible need for climate engineering; the specific concept descriptions were matched for pictorial content, concept elaboration, concept length, and the positive and negative aspects of the description; the pictures selected represented attempts by experts to present each technique, and were matched for size, colour, complexity and labels (although no attempt is made to evaluate visual processing, the inclusion of concept pictures was necessary to reduce the risk that some semantic elements of the concept statement become over-salient[31]); to minimize fatigue, each participant evaluated only four concepts; to minimize item order effects, the order of presentation of both concepts and adjectives was rotated; to avoid priming responses through stimulus frequency, the attributes were balanced between positive and negative adjectives; to avoid self-generated validity effects, the concept descriptions did not use the adjectives allocated to attribute measurement; to check the adequacy of the concept descriptions, participants were asked whether they could explain the concept to somebody else; for quality control, the questionnaire was checked by experts and pre-tested with members of the online panel.

The concept presentations were adequate: 37–50% of participants agreed that they could explain each concept to somebody else; 34–45% were neutral; whereas, only 18–24% disagreed.

The tendency of attributes to access the same memory structures was assessed using Kendall Tau-b correlations (Supplementary Table 5)[19]. As a result, the attributes unpredictable and beneficial were dropped from further analysis. In commercial research, negative attributes are often dropped as they fail to discriminate between users and non-users[27]. In this case they are retained, as all participants are non-users and the usage effect in brand image association rates is not relevant. Quick-fix is counted as a negative attribute, as this was the perception during the qualitative phase. In addition, quick-fix predominantly correlates positively with negative attributes and negatively with positive attributes (Supplementary Table 5).

There were three treatments within each survey, resulting in minor sample size variation. There were no significant differences in the net positive variable between treatments (Supplementary Table 4). We report raw numbers for the net positive variable (Table 2) but otherwise normalize sample sizes to the value in the largest subsample (Table 1 and Figs 1 and 2). All statistical tests are conducted on unadjusted numbers.

Received 21 July 2013; accepted 2 December 2013; published online 12 January 2014

References

1. *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Geoengineering* (Potsdam Institute for Climate Impact Research, 2012); http://www.ipcc.ch/pdf/supporting-material/EM_GeoE_Meeting_Report_final.pdf

2. Corner, A. & Pidgeon, N. F. Geoengineering the climate: The social and ethical implications. *Environ. Sci. Policy Sustain. Dev.* **52,** 24–37 (2010).
3. Shepherd, J. Geoengineering the climate: An overview and update. *Phil. Trans. R. Soc. A* **370,** 4166–4175 (2012).
4. The Royal Society. *Geoengineering the Climate Science, Goverance and Uncertainty* Science Policy Centre Report 10/09 (The Royal Society, 2009).
5. Pidgeon, N. Climate change risk perception and communication: Addressing a critical moment? *Risk Anal.* **32,** 951–956 (2012).
6. *Large-Scale Intentional Interventions into The Climate System? Assessing the Climate Engineering Debate* (Kiel Earth Institute, 2011); http://www.fona.de/mediathek/pdf/Climate_Engineering_engl.pdf
7. Peters, G. P. *et al.* Rapid growth in CO_2 emissions after the 2008–2009 global financial crisis. *Nature Clim. Change* **2,** 2–4 (2011).
8. Vaughan, N. & Lenton, T. A review of climate engineering proposals. *Climatic Change* **109,** 745–790 (2011).
9. Pidgeon, N. & Fischhoff, B. The role of social and decision sciences in communicating uncertain climate risks. *Nature Clim. Change* **1,** 35–41 (2011).
10. *Experiment Earth: Report on a Public Dialogue on Geoengineering* (Ipsos Mori, 2010); http://www.nerc.ac.uk/about/consult/geoengineering-dialogue-final-report.pdf
11. Orr, P., Twigger-Ross, C., Kashefi, E., Rathouse, K. & Haigh, J. *Evaluation of Experiment Earth? Public Dialogue on Geoengineering* (Collingwood Environmental Planning, 2011). http://www.nerc.ac.uk/about/consult/geoengineering-evaluation-report.pdf
12. Pidgeon, N., Parkhill, K., Corner, A. & Vaughan, N. Deliberating stratospheric aerosols for climate geoengineering and the SPICE project. *Nature Clim. Change* **3,** 451–457 (2013).
13. Macnaghten, P. & Szerszynski, B. Living the global social experiment: An analysis of public discourse on solar radiation management and its implications for governance. *Global Environ. Change* **23,** 465–474 (2013).
14. Mercer, A., Keith, D. & Sharp, J. Public understanding of solar radiation management. *Environ. Res. Lett.* **6,** 044006 (2011).
15. *Climate Engineering Technical Status, Future Directions, and Potential Responses* GAO-11-71 (US Government Accountability Office, 2011); http://www.gao.gov/search?q=_GAO-11-71
16. Pidgeon, N., Corner, A., Parkhill, K., Spence, A., Butler, C. & Poortinga, W. Exploring early public responses to geoengineering. *Phil. Trans. R. Soc.* **370,** 4176–4196 (2012).
17. Keller, K. L. Conceptualizing, measuring, and managing customer-based brand equity. *J. Market.* **57,** 1–22 (1993).
18. Henderson, G. R., Iacobucci, D. & Calder, B. J. Brand diagnostics: Mapping branding effects using consumer associative networks. *Eur. J. Oper. Res.* **111,** 306–327 (1998).
19. Romaniuk, J. Modeling mental market share. *J. Business Res.* **66,** 188–195 (2013).
20. Anderson, J. R. & Bower, G. H. *Human Associative Memory* (Hemisphere, 1973).
21. Anderson, J. R. A spreading activation theory of memory. *J. Verbal Learn. Verbal Behav.* **22,** 261–295 (1983).
22. Lees, G. & Wright, M. The effect of concept formulation on concept scores. *J. Prod. Innov. Manage.* **21,** 389–400 (2004).
23. Pidgeon, N., Harthorn, B. H., Byrant, K. & Rogers-Hayden, T. Deliberating the risks of nanotechnologies for energy and health applications in the United States and United Kingdom. *Nature Nanotech.* **4,** 95–98 (2008).
24. Corner, A. & Randall, A. Selling climate change? The limitations of social marketing as a strategy for climate change public engagement. *Glob. Environ. Change* **21,** 1005–1014 (2011).
25. Kahneman, D. *Thinking, Fast and Slow* (Penguin, 2011).
26. Driesener, C.B. & Romaniuk, J. Comparing methods of brand image measurement. *Int. J. Market Res.* **48,** 681–698 (2006).
27. Winchester, M. & Romaniuk, J. Evaluative and descriptive patterns to negative image attributes. *Int. J. Market Res.* **45,** 21–34 (2003).
28. Sharp, B. *How Brands Grow: What Marketers Don't Know* (Oxford Univ. Press, 2010).
29. Hwang, Y. & Southwell, B. G. Science TV news exposure predicts science beliefs. *Commun. Res.* **36,** 724–742 (2009).
30. Parkhill, K. & Pidgeon, N. *Public Engagement on Geoengineering Research: Preliminary Report on the SPICE Deliberative Workshops* Understanding Risk Group Working Paper 11-01 (School of Psychology, Cardiff University, 2011).
31. Wright, M., Gendall, P. & Lewis, A. Making survey based price experiments more accurate. *J. Market Res. Soc.* **41,** 245–249 (1999).

Acknowledgements

This work was supported by the Massey University Research Fund (M.J.W.) and NERC grant NE/I006311/1 (D.A.H.T.). Thanks to M. Comrie, P. Gendall and L. Stocchi for helpful and thought-provoking suggestions.

Author contributions

D.A.H.T. conceived of the project, advised on the climate engineering concepts and contributed to writing. M.J.W. developed the research design, raised funds and undertook analysis and writing. P.M.F. managed the fieldwork and contributed to analysis and writing.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.J.W.

Competing financial interests

The authors declare no competing financial interests.