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How Negative Frames Can Undermine Public Support for Studying Solar Geoengineering in the U.S

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Scientists and policymakers have become interested in the viability of solar geoengineering as a way to manipulate the Earth's temperature in the face of unabated global warming. This paper reports the results from a survey experiment designed to test predictions about the effects of exposure to framed messages about basic scientific research on solar geoengineering. Our findings reinforce other survey research showing that solar geoengineering is a generally unfamiliar concept, but also show that this topic has not yet become politicized. In addition, despite treatments of equal valence, we find that negative information can exert a more powerful influence than positive information on support for establishing a research program to study solar geoengineering. The results have implications for understanding how framing can influence public support for research on new technologies to mitigate climate change.

Keywords: solar geoengineering, public opinion, framing, climate engineering (CE), politicization

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INTRODUCTION

Researchers and policymakers have become interested in the viability of engineering interventions to manipulate the Earth's temperature in the face of unabated global warming (Moreno-Cruz and Keith, 2013; Keith and Irvine, 2016; Bellamy & Healey, 2018; Horton et al., 2018). A report on "Reflecting Sunlight," released in May 2021 by the U.S. National Academies of Science, Engineering and Medicine (NASEM), recommended that the U.S. spend $200 million dollars over 5 years to establish a research program to study the potential for solar geoengineering strategies to "moderate warming by increasing the amount of sunlight that the atmosphere reflects back to space" or to "reduce the trapping of outgoing thermal radiation." These strategies include "adding small reflective particles to the upper atmosphere to reflect sunlight, increasing relative cloud cover in the atmosphere (and) thinning high-altitude clouds" that trap heat (NASEM, 2021).

Response to the NASEM report included calls for more social science research, and more attention to the governance of the research agenda itself (Jennie et al., 2021; Stephens et al., 2021). McLaren and Corry (2021) noted that solar geoengineering research itself could condition policy outcomes, calling for a "reflexive research governance regime developed with international participation" and encompassing the social sciences. Keith (2021) suggested a taxonomy on which "constructive disagreements" about solar geoengineering research could be organized, and Aldy et al. (2021) suggested a research agenda that would include the social sciences. To date, there have been few studies on the public's views concerning doing research on, funding research for, or implementing solar geoengineering technologies (Bellamy et al., 2016; Buck, 2016; Merk et al., 2016; Wagner and Merk, 2019; Nelson et al., 2021). Additionally, only a handful of studies have tested the impact of exposure to framed messages about solar geoengineering on the U.S. public's related beliefs

(e.g., Corner & Pidgeon, 2015; Bellamy et al., 2016; Fairbrother, 2016; Merk et al., 2016; Mahajan et al., 2019; Raimi et al., 2021). Nor have any studies, to our knowledge, evaluated response to framed messages about climate engineering technologies across different contexts, such as in a setting where basic scientific research is politicized or competing messages are presented (Druckman, 2017; Chinn et al., 2020).

The purpose of the research reported here is to evaluate how exposure to framed messages about research on solar geoengineering affects support for the establishment of a targeted research program in the U.S. We extend research on message framing effects and public perceptions regarding solar geoengineering by: 1) evaluating the effect of both positive and negative framed messages in isolation and competitive rhetorical settings to better understand the dynamics of public support for funding basic scientific research on solar geoengineering; and 2) testing the impact of these framed messages in distinct settings that either politicize science or highlight the benefits and legitimacy of science. Hypotheses about the influence of exposure to positive and negative frames about solar geoengineering were tested in an experiment embedded in a survey implemented by Qualtrics on a large and diverse sample of Americans in July 2021. We next provide a description of solar geoengineering approaches that have been discussed recently by various scientific organizations before reviewing research on framing effects that motivate the predictions that were tested in an original survey experiment. We conclude by discussing the implications of the findings and avenues for future research.

WHAT IS SOLAR GEOENGINEERING?

The subject of this research is solar radiation management, also referred to as "solar geoengineering" (NAS, 2021, p. 21), including increasing the reflectivity of the Earth, for example by painting surfaces white to reflect the sun, the enhancement of the reflectivity of clouds, the injection of sulfuric aerosols into the stratosphere to create shade, or the launching of shields or mirrors into space to reflect solar energy. In 2012, the Intergovernmental Panel on Climate Change expert meeting on geoengineering endorsed this categorization (IPCC, 2012). Solar radiation management itself can be subdivided into sub-categories. The National Academies (2021) report noted that solar geoengineering strategies can include placing reflective materials such as mirrors above the Earth's atmosphere, or altering the reflectivity of the Earth's land, sea, and ice surfaces. Their report, however, focused on three atmospheric-based strategies: stratospheric aerosol injection (SAI), a process analogous to volcanic eruptions wherein sulfur is injected into the atmosphere to "scatter sunlight, resulting in an increase in the ratio of diffuse to direct light reaching Earth's surface" (National Academies, 2021, p. 44), marine cloud brightening (MCB) through the addition of aerosols to increase the albedo or reflectivity of the clouds, and cirrus cloud thinning (CCT) in the upper atmosphere to increase the radiation of longwave energy from the Earth.

FRAMING AND SUPPORT FOR SOLAR GEOENGINEERING

Public support for emergent scientific innovations and technologies is often influenced by exposure to framed messages (Corner & Pidgeon, 2015; Druckman & Bolsen, 2011; Gamson & Modigliani, 1989). A *frame in communication* is defined as a word, phrase, image, or symbol that highlights a subset of potentially relevant considerations toward any attitude object (Druckman, 2001). In this sense, "frames" are endemic to human communication because they "compress" information into understandable "chunks" that allow people to process (scientific) information (Nisbet, 2009). Frames transmitted through media coverage help the public understand social problems, assign blame, and identify solutions (Entman, 1993). When individuals are exposed to a communication (e.g., a news story) that emphasizes a particular way of thinking about an issue or topic, this "interpretation" or "frame" becomes more cognitively accessible and may be relied on more heavily (i.e., assigned more "weight") than otherwise would have been in the absence of exposure to the communication; this is called an *emphasis framing effect* (Druckman, 2001).[1] Framing theory illustrates that a person's attitude toward any object is a function of the *salience and weight* assigned to various considerations that are available when an opinion is formed (Chong & Druckman, 2007).

Several studies in the U.S. and United Kingdom have explored how exposure to framed messages influence public opinion about solar geoengineering interventions (e.g., Corner & Pidgeon, 2015; Bellamy et al., 2016; Fairbrother, 2016; Merk et al., 2016; Mahajan et al., 2019; Raimi et al., 2021). When people are unfamiliar with a concept, its framing may have a particularly strong influence (Druckman & Lupia, 2017), an effect that Raimi et al., 2021 documented. As Mahajan et al. (2019) explain, "Familiarity with solar geoengineering in Western Europe, Canada, and the United States—the regions best studied to date—remains low. Estimates range from 2–20% of the population knowing about solar geoengineering … Fewer still can define it … However, once offered information about solar geoengineering, subjects are able to distinguish between its use and research, and they hold divergent views about the two" [p. 527, also see Burns et al., (2016); Corner et al., (2013); Mercer et al., (2011); Klaus et al., (2021)].

Mahajan et al. (2019) conducted a framing study in the context of the of the 2016 Cooperative Congressional Election Study (CCES). They found that most of the respondents reported that they were "not at all" or "a little" familiar with solar geoengineering. Regardless of their reported familiarity, respondents were then randomly assigned to one of three frames that varied the degree to which solar geoengineering was characterized as a "natural" or "unnatural" process to evaluate its effect on 1) support for the use of

[1]We focus exclusively on emphasis framing and not equivalency framing effects (Tversky & Kahneman, 1981), which occur when information that is positive or negative in valence generates unconscious information processing biases in preference and opinion formation (Levin, Schneider, & Gaeth, 1998).

solar geoengineering and 2) whether more research should be done on it. The results, surprisingly, showed that the way in which solar geoengineering was described (i.e., framed) had no effect on respondents' support for its use or research into these approaches.[2] However, pre-existing beliefs that the technology was a relatively quick and cost-effective way to address climate change was associated with higher levels of support, while perceptions that it would have unintended negative consequences was associated with decreased support. The survey also revealed relatively high levels of support for the use of solar geoengineering (67%) and for research into these approaches (81%).

Empirical experiments on the framing of solar geoengineering have yielded mixed results. Raimi et al. (2021) evaluated responses to exposure to one of four brief newspaper articles about solar geoengineering embedded in a survey that included three framed messages about the technology: that it is a major solution in which "we wouldn't have to do much more to stop the worst effects of climate change", a temporary (minor) solution in which we would "have to do more to stop the worst effects of climate change", or a risky technology frame that emphasized "playing with the climate at such a grand scale could be disastrous" (p. 303). The results indicated that exposure to the frames had little effect on liberal respondents' concern about or belief in human-caused climate change; however, conservatives and moderates who were exposed to any of the treatments expressed weaker beliefs in climate change compared to respondents in the control condition. This suggests that concern that solar geoengineering might result in a "moral hazard" whereby people become less supportive of action to address climate change if they believe there is a "techno-fix." However, several other experiments have demonstrated treatment effects in the *opposite* direction with conservatives and/or those who value individualism and hierarchy becoming more likely to express a belief in anthropogenic climate change and/or more willing to support climate mitigation policies following exposure to information about solar geoengineering technologies to combat climate change [Kahan et al., (2015); Fairbrother, (2016)]. More work is needed to determine how much differences in the content of the messages versus the composition of the samples may have driven these divergent results.

The few existing studies discussed above focus on "very brief descriptions of [solar geoengineering]" and have called for future research that accounts for the fact that, "in the real world, news consumers are likely to encounter much more detailed explanations of SRM, including more details on potential technologies and techniques, or explication of tradeoffs, and more coverage of uncertainties" (Raimi et al., 2021, p. 312). Based on a voluminous literature that has demonstrated that exposure to framed messages that emphasize the *benefits or costs* of an emergent technology can shift public opinion in the direction of the framed message, we offer the following pre-registered predictions:[3]

HYPOTHESIS 1 | Exposure to a framed message that emphasizes the benefits of solar geoengineering will increase individuals' (a) support for a research program to study it in the U.S. and (b) perceptions that solar geoengineering approaches will be used in the future to reduce Earth's temperature, as well as (c) reduce reported anxiety about the research program.

HYPOTHESIS 2 | *E*xposure to a framed message that emphasizes the risks of solar geoengineering will decrease individuals' (a) support for a research program to study it in the U.S. and (b) perceptions that solar geoengineering approaches will be used in the future to reduce Earth's temperature, as well as (c) increase reported anxiety about the research program.

People are often presented with multiple consideration about any issue or topic when forming their opinion in the real world. For instance, a news story about solar geoengineering research might describe its potential benefits while also highlighting the possibilities for unintended consequences that might result from widespread deployment. Yet most research on framing effects and science communication focuses on how exposure to a single frame, encountered in isolation, influences people's related beliefs. We are not aware of any research that has tested the impacts of exposure to competitive messages about the benefits and costs of solar geoengineering; however, in previous research on other topics, when frames of "equal strength" that differ in "direction" are pitted against one another in "rhetorical competition," the independent influence of each frame "cancels out" the impact otherwise observed from exposure to the frame in isolation (Chong & Druckman, 2007; Sniderman & Theriault, 2018). Therefore, we offer the following prediction.

HYPOTHESIS 3 | Exposure to a framed message that emphasizes the benefits and risks of solar geoengineering research will lead the independent effects of each frame to "cancel out" and exert no impact on support for solar geoengineering research.

FRAMING IN THE CONTEXT OF POLITICIZATION OR PROMOTION OF SCIENCE

Science is easily "politicized" because of its inherent uncertainty (Druckman, 2017). Bolsen, Druckman, and Cook (2014) state, "Few trends in science have received as much attention as has its politicization—that is, *when political interests* shape the presentation of scientific facts to fit distinct models of 'reality' for self-interested reasons" (p. 4, emphasis added). Politicization creates uncertainty about whether scientific evidence or arguments can be trusted in any setting and heightens the reported anxiety people report feeling toward emergent scientific technologies, thus weakening the credibility and impact of positive (e.g., consensus) scientific information, stunting public support for emergent scientific technologies and exacerbating

[2]We concur with the authors' assessment (Fn. 6, pg. 538) that the finding is "surprising" given that others have argued that: "Framing may be particularly effective in current discussions of geoengineering, as the public is still largely unfamiliar with these technologies" (Raimi et al., 2021, p. 302).

political polarization on many issues [Bolsen & Druckman, (2015); Gauchat, (2012); McCright & Dunlap, (2011); Oreskes & Conway, (2011].

Bolsen, Druckman, and Cook (2014) found that exposure to politicization attacking a scientific consensus report in support of the development of a clean energy technology eliminated the positive impact of the message and increased respondents' anxiety about its deployment. The study also employed an "intriguing counterfactual frame to politicization" that emphasized the promise of the scientific method that stated, "scientific research involves the systematic gathering of observable, measurable, and replicable evidence—as such, it provides a relatively objective and unbiased basis for new innovations" (p.5). The results showed that the inclusion of this "promise of science" frame increased respondents' trust in science, led to greater optimism towards science, and enhanced the impact of a positive "environmental frame" on individuals' support for the development of the clean energy technology. The presence of a distinct, positively valanced frame emphasizing the objectivity and importance of basic science research bolstered the impact of scientific arguments when used to advocate for research or deployment of a novel technology. Overall, this research shows that the effect of framed messages on public support for emergent scientific technologies can be contingent on the contexts in which those messages are encountered and whether science is politicized or characterized as unbiased and objective. Therefore, we offer the following predictions.

HYPOTHESIS 4 | Exposure to a framed message that emphasizes the benefits of solar geoengineering, in a context where the benefit of scientific research is also highlighted, will increase (a) support for a research program to study it in the U.S. and (b) perceptions that solar geoengineering approaches will be used in the future to reduce Earth's temperature, as well as (c) reduce reported anxiety about the research program.

HYPOTHESIS 5 | Exposure to a framed message that emphasizes the benefits of solar geoengineering, in a context where the politicization of scientific research is also highlighted, will result in no opinion change due to politicization weakening or eliminating the positive frame's impact.

HYPOTHESIS 6 | Exposure to a framed message that emphasizes the risks of solar geoengineering, in a context where the politicization of scientific research is also highlighted, will decrease (a) support for a research program to study it in the U.S. and (b) perceptions that solar geoengineering approaches will be used in the future to reduce Earth's temperature, as well as (c) increase reported anxiety about the research.

HYPOTHESIS 7 | Exposure to a framed message that emphasizes the risks of solar geoengineering, in a context where the promise of scientific research is also highlighted, will result in no opinion change due to the pro-science frame weakening or eliminating the negative frame's impact.

PARTISANSHIP AS A MODERATOR OF FRAMING SOLAR GEOENGINEERING?

Response to any framed message associated with actions or policies to address climate change may depend on factors such as party identification given the high levels of polarization surrounding its science in the U.S. (Hart & Nisbet, 2012; Egan & Mullin, 2017). Various information processing motivations—such as a "directional motivation" (i.e., any motive besides "accuracy") to protect one's core values [Wolsko et al., (2016); Bayes et al., (2020)], uphold prior beliefs (Kunda, 1990), bolster an existing (e.g., partisan) identity (Kahan, 2016), or avoid policies or regulations that could impose restrictions on personal freedoms (Lewandowsky et al., 2013; Campbell & Kay, 2014)—can influence people's receptivity to framed messages. Moreover, even if an accuracy motivation is the underlying goal being pursued when evaluating new information, polarization can still develop because of differences in the perceived credibility of the content of any communication (e.g., trust in the messenger) [Druckman & McGrath, (2019); also see; Bolsen, Palm, & Kingsland, (2019)].

Although the U.S. public is largely unfamiliar with solar geoengineering, a nationally representative survey in 2018 showed that liberal Democrats were more likely than conservative Republicans to agree that "solar geoengineering would make a difference in reducing the effects of climate change" (64% versus 20%, respectively); further, a majority of conservative Republicans believed that it would "do more harm than good" for the environment Funk et al., (2018). Kahan et al. (2015) found, however, that conservatives were more open to a framed message about climate change after learning about geoengineering (i.e., after reading a story advocating for greater investments into geoengineering as a "necessary and effective" alternative to stricter pollution regulations, p. 197) because it seems to offer a means of avoiding regulatory responses to climate change. Similarly, geoengineering may be more amendable to values such as support for free markets, which may lead conservatives to believe more in climate change and make them willing to consider mitigation measures [Campbell & Kay, (2014); Gillis et al., (2021)]. Given the dearth of research on framing and support for solar geoengineering in different information environments, we evaluate the following preregistered research question:

Research Question 1: Does party identification moderate the effect of the pro- or con-frames in isolation and/or in competitive information environments?

SURVEY EXPERIMENT

We implemented a survey experiment in which we randomly assigned 1,075 respondents, recruited by Qualtrics, to one of eight experimental conditions that varied the headline and content of a short "news article" with information about proposed research to study solar geoengineering. The survey was implemented in July 2021 and included quotas for party identification, gender, race

TABLE 1 | Experimental Design and Hypotheses.

Condition	Headline	Prediction/Question
Control (n = 120)	**Solar geoengineering** (definition only)	*Baseline*
Pro Frame (n = 131)	**Top American scientists recommend studying solar geoengineering**	*H1: Increased support*
Con Frame (n = 134)	**Controversial report recommends studying solar geoengineering**	*H2: Decreased support*
Pro & Con Frame	**Solar geoengineering**	*H3: No change*
(n = 136) Pro Frame & Science Benefits	**Top American scientists recommend studying solar geoengineering**	*H4: Increased support*
(n = 145) Pro Frame & Politicization (n = 149)	**Top American scientists recommend studying solar geoengineering**	*H5: Reduced impact of Pro frame*
Con Frame & Politicization (n = 128)	**Controversial report recommends blocking the sun with dust**	*H6: Decreased support*
Con Frame & Science Benefits (n = 132)	**Controversial report recommends studying solar geoengineering**	*H7: Reduced impact of Con frame*

and geographic region.[4] These quotas resulted in a distribution of other demographic characteristics that is remarkably similar to that of the U.S. population (**Supplemental Material A1**). For example, the 2021 U.S. Census reports that 27.9% of Americans over the age of 25 had a high school diploma as their highest level of school completed (U.S. Census Bureau, 2021), while our survey had 23.1% in that category. Similarly, the census reported that 23.5% had a bachelor's degree as their highest degree and 14.4% had an advanced degree, while our survey had 25.2% and 16.2% in those categories respectively.

Participants were informed at the beginning of the survey that the research had been approved by an IRB and provided their consent by proceeding to the next page. After answering several demographic questions, everyone was informed that they would read a "short article and answer some questions about an approach to reduce the average global temperature that you may not be familiar with—solar geoengineering." Given the public's general lack of familiarity with solar geoengineering technologies, it was deemed necessary to include a short definition for all respondents to provide some context to express an opinion, including those respondents randomly assigned to the "control" (n = 120) or baseline condition (**Table 1**). The "control" condition, therefore, included a "neutral" headline, "Solar geoengineering," and explained that it "*includes a variety of ways people can cool the planet by reflecting some sunlight away from the Earth and back out to space. This can be done by making clouds whiter and brighter, by putting mirrors into space to reflect sunlight, or by increasing cloud cover by putting small particles into the stratosphere to block some of the sunlight from Earth*." Respondents in the control condition then proceeded to answer the primary dependent measures.

Participants randomly assigned to the *Pro frame* (n = 131) condition viewed the headline, "*Top American scientists recommend studying solar geoengineering*," followed by the definition used in the baseline with an additional paragraph that referenced: a "*consensus report*" published in May 2021 "*urging that we study solar geoengineering to learn more about its potential for reducing global temperatures (and that it) could provide a fast, effective and relatively inexpensive way to buy valuable time to work on sustainable ways to stabilize the climate*." The content and headlines for the experimental stimuli were based on information contained in the NAS report and news articles published in the U.S. in 2020 and 2021. The complete wording of the treatments for all experimental conditions is available online in the **Supplemental Appendix**.

Participants randomly assigned to the *Con frame* (n = 134) condition viewed the headline, "*Controversial report recommends studying solar geoengineering*," followed by the definition used in the baseline with an additional paragraph that referenced: a "*controversial report*" that was recently released by American scientists that had recommended funding for solar geoengineering. It stated that "*other scientists are concerned about the risks in blocking incoming sunlight in this way (and that it) could change rainfall patterns, threaten wildlife, cause droughts and famines, and harm the ozone layer*." The headlines and content for this message were again based on actual news articles published prior to when the survey was fielded.

We conducted a pre-test of the *Pro* and *Con* frames on 102 respondents recruited from Amazon's Mechanical Turk (MTurk) on 12 July 2021. We asked participants to rate the "direction" of the arguments (1 = *completely opposed to the research*; 7 = *completely supportive of the research*) on a 7-point scale and found that the Pro frame message was rated (5.62) and the *Con* frame message was rated (2.91). The same group of respondents also rated the perceived "effectiveness" of each message, regardless of their own opinion about solar geoengineering research, on a 7-point scale (1 = *completely ineffective*; 7 = *completely effective*, 4.92 and 4.81 means for the pro- and con-message, respectively). The results from this manipulation check indicated that the frames were perceived in the direction that they were intended and that they were rated identical in terms of "effectiveness" or "frame strength" (both were rated as "somewhat effective" ~ 5 mean scores on the 7-point scale).[5]

Respondents randomly assigned to the *Pro & Con Frame* (n = 136) condition viewed a "neutral" headline identical to what appeared in the baseline, "*Solar geoengineering*," but were then exposed to both the *Pro*- and *Con*-frames within the same short article. The language in the stimuli was identical to what is described above for each frame with small wording changes to link the two together in a competitive framing condition. In this

[4]We were limited to 4 quotas for demographic characteristics by the survey provider; nonetheless, we obtained a diverse sample that was comparable on variables such as respondent education and income.

[5]All pre-test results are available upon request from the authors.

condition, the order in which the frames appeared was held constant with the positive benefits supporting solar geoengineering research coming before the negative considerations about the potential risks.

Respondents randomly assigned to the *Pro Frame & Scientific Benefits* (n = 145) condition viewed the same headline and content described above for those in the Pro frame condition along with a message emphasizing the benefits of scientific research: "*Scientific research can help us develop new technologies, solve practical problems, and make more informed decisions. This happens through the systematic gathering and evaluation of evidence that accumulates over time. Solar geoengineering research will lay the groundwork for us to better understand whether these approaches should be considered as one of the tools in our toolkit in the fight against the damaging effects of climate change.*"

Alternatively, respondents randomly assigned to the *Pro Frame & Politicization* (n = 149) condition also viewed the same headline and content included in the *Pro frame* condition, but with an additional paragraph that stated: "*Politics can often shape and distort both the direction and the quality of any research. Supporters and detractors will selectively use facts and cite evidence that supports their agendas from a few small tests on solar geoengineering conducted by laboratory scientists. This will limit what can be learned about the safety and effectiveness of using these risky approaches on a widespread scale to alter global temperatures.*"

Respondents randomly assigned to the *Con Frame & Politicization* (n = 128) condition and the *Con Frame & Scientific Benefits* (n = 132) condition were exposed to identical frames as described above that either include the *Con frame* situated in a context that reinforced uncertainty about scientific research—that is, in a politicized context—or in a context in which the benefits of scientific research were highlighted, potentially lessening the impact of the message when it is encountered in isolation.

Dependent Variables

After reading a version of the short paragraph on solar geoengineering, participants reported the extent to which they supported "the US funding a research program to study solar geoengineering" on a 7-point scale (1 = *strongly opposed; 7 = strongly support*). We also asked respondents if they think that "research into solar geoengineering will have positive or negative consequences" on a 7-point scale (1 = *extremely negative*; 7 = *extremely positive*). Following our preregistration plan, we combined these two items into a reliable index (α = .87), to measure *support for funding* solar geoengineering research. Next, we measured respondents' perceptions about the likelihood that "solar geoengineering approaches will be used to reduce Earth's temperatures in the future" on a 7-point scale (1 = *extremely unlikely*; 7 = *extremely likely*). Finally, politicization and negative frames about solar geoengineering were expected to increase anxiety given the existing research linking potentially "threatening information" about emergent technologies with increased levels of anxiety; therefore, we asked respondents, "How much anxiety do you feel when you think about research to study solar geoengineering" on a 5-point scale (1 = *none*; 5 = *a great deal*).

RESULTS

To test our hypotheses, we estimate a collection of OLS regression models with robust standard errors. We regress each dependent variable on our condition indicators, omitting the *Control* condition as the reference group. The results of our analysis are reported in **Table 2**.[6]

Our first set of hypotheses was that exposure to a framed message emphasizing the benefits of solar geoengineering by "top American scientists" would increase support for the research and perceptions that it would be used in the future to counter the effects of global warming, as well as reduce anxiety about it (H1a-H1c). We find weak and mixed support for these predictions: respondents in the pro-frame condition were not more supportive of funding solar geoengineering research relative to those in the control condition (column 1, **Table 2**). There was also no effect of the positively framed message on belief that these approaches would be deployed in the future to alter the Earth's temperature. However, in support of H1c, individuals who were exposed to the pro-frame in isolation were significantly less anxious about research on solar geoengineering (b = *-0.31*, p = *0.04*). The mean response across experimental conditions for each dependent variable are also reported in **Table 3** to aid in interpretation of the impact of the randomized experimental treatments relative to the baseline (control) condition. Not surprisingly given the public's general lack of familiarity with solar geoengineering support for these interventions in the absence of any information is close to the midpoint ("not sure") on the response scales for each outcome measure.

Our second set of hypotheses was that exposure to a framed message emphasizing the risks of solar geoengineering and scientific controversy over funding the research would reduce support for its funding while increasing anxiety (H2a-H2c). We find clear evidence in support of this set of hypotheses across all dependent measures (row two, **Table 2**). Exposure to the con-frame reduced support for funding a solar geoengineering research program (b = *-0.85*, p = *0.01*) and perceptions that the technology would be deployed in the future to fight climate change (b = *-0.70*, p = *0.01*), while also increasing anxiety about the research (b = *0.29*, p = *0.05*). The substantive movement on

[6]As an additional test, we re-estimated our empirical models with several demographic and political covariates included. The results are reported in **Supplemental Table A2** (available online). We do not report these models in our main analysis for two reasons. First, we conducted a randomized experiment, and given that the randomization procedure was successfully implemented, the inclusion of individual level covariates should not change the substantive conclusions derived from results we report. And second, our theoretical framework and hypotheses are primarily concerned with examining the effects of the experimental manipulations on our dependent measures. However, as reported in **Supplementary Table A2**, our results are robust to alternative specification. Additional analyses using alternative model specifications are included in the online.

TABLE 2 | *Main Treatment Effects*.

	Funding	*p-value*	Used	*p-value*	Anxiety	*p-value*
	Coef		*Coef*		*Coef*	
Pro frame	0.15	0.40	-0.27	0.17	–0.31**	0.04
	(0.18)		(0.20)		(0.15)	
Con frame	–0.85***	0.00	–0.70***	0.00	0.29*	0.05
	(0.18)		(0.20)		(0.15)	
Pro + Con frame	–0.60***	0.00	–0.50**	0.01	0.35**	0.02
	(0.18)		(0.20)		(0.15)	
Pro + Science promise	0.10	0.57	–0.07	0.70	-0.18	0.23
	(0.18)		(0.20)		(0.15)	
Con + Science promise	–0.36**	0.04	–0.32*	0.09	0.08	0.61
	(0.18)		(0.19)		(0.15)	
Pro + Politicization	–0.07	0.72	–0.11	0.60	–0.13	0.39
	(0.18)		(0.20)		(0.15)	
Con + Politicization	–0.88***	0.00	–0.84***	0.00	0.38**	0.01
	(0.18)		(0.20)		(0.15)	
Constant (Control)	4.42***	0.00	4.31***	0.00	2.20***	0.00
	(0.13)		(0.14)		(0.11)	
N	1075		1075		1075	
AIC	3839.2		4050.0		3467.6	
BIC	3879.0		4089.8		3507.5	

Cell entries are OLS, coefficients with standard errors in parentheses below; Two-tailed p-values are shown in the adjacent column. Coefficients represent the difference in means between the treatment condition and the Control group baseline. Stars indicate a statistically significant coefficient estimate using a two-tailed test. *p < 0.10, **p < 0.05, ***p < 0.01.

the response scales due to the experimental conditions roughly reflects the size of the regression coefficient in each cell (relative to the "*Constant*" term, which represents the mean score on the response scale in the baseline condition). In other words, exposure to negative arguments that highlighted the risk of solar geoengineering approaches to alter the Earth's temperature decreased support for funding a research program by almost one full point on the 7-point response scale (also see the condition means reported in **Table 3**).

We next evaluate the impact of exposure to both the pro- and con-frame in competition on the outcome measures (row 3, **Table 2**). Counter to our prediction (H3), and even though we pre-tested the frames for direction and strength, their impacts did not "cancel out" when juxtaposed in competition. Instead, the negative information about the potential risks of solar geoengineering overpowered the positive considerations, and respondents were less supportive of funding research to study these approaches ($b = -0.60$, $p = 0.01$), viewed them as less likely to be used in the future ($b = -0.50$, $p = 0.01$), and were more anxious about research in this area ($b = 0.35$, $p = 0.02$).

In addition to testing predictions about the impact of pro- and con-frames in isolation and direct competition, we also expected that each frame's effect would be conditioned by the presence of "science politicization" or a "science benefits" frame that was either congruent with or incongruent to the pro- or con-frame respectively. Hypothesis 4 predicted that emphasizing the positive benefits of solar geoengineering in a context where the promise of scientific research was also emphasized would increase support relative to the baseline. We find no support for this prediction across any of the dependent variables (row 4, **Table 2**). This may not be surprising given the weak effect of the pro-frame in isolation. The hypothesis 5 that predicted that the presence of science politicization would weaken or eliminate the impact of the pro-frame on the outcome measures was partial supported insofar as the positive effect that the pro-frame exerted in isolation on lowering anxiety about the research disappears when that frame is encountered in a context where science is politicized (row six, **Table 2**).

The impact of the *Con frame* in distinct contexts where scientific research is politicized or bolstered was assessed. Hypothesis 6 predicted that the *Con frame* appearing in a context that also politicized the scientific research (*Con + Politicization*) would have a negative effect on our first two dependent measures but increase anxiety relative to the control condition. In support of H6, participants exposed to the *Con frame* in a context where science was politicized (row 7, **Table 2**) were less supportive of funding a research program ($b = -0.88$, $p = 0.01$), less likely to say that these tools would be used in the future ($b = -0.84$, $p = 0.01$), and more anxious about research in this area ($b = 0.38$, $p = 0.01$). The effect sizes are slightly larger for each outcome measure compared to what is observed in the *Con frame* in isolation, but not statistically different (**Supplementary Tables A6, A7** in). In other words, the presence of politicization did not significantly enhance the negative impact that was observed by the *Con frame* in isolation. Conversely, in looking at the effect of the *Con frame* in a context where the benefits of scientific research are accentuated (row 5, **Table 2**), Hypothesis 7 predicted that the context would weaken or eliminate the effect of the *Con frame* in isolation. We find clear support for this prediction: even though respondents were less supportive of funding the

TABLE 3 | Mean Responses Across experimental conditions.

Condition		(1) Funding	(2) Used	(3) Anxiety
Control	Mean	4.42	4.31	2.20
	SD	(1.37)	(1.38)	(1.19)
	N	120	120	120
Pro frame	Mean	4.57	4.04	1.89
	SD	(1.29)	(1.50)	(1.12)
	N	131	131	131
Con frame	Mean	3.57	3.60	2.49
	SD	(1.52)	(1.58)	(1.31)
	N	134	134	134
Pro + Con frame	Mean	3.81	3.81	2.55
	SD	(1.48)	(1.74)	(1.28)
	N	136	136	136
Pro + Science promise	Mean	4.52	4.23	2.02
	SD	(1.35)	(1.49)	(1.15)
	N	145	145	145
Con + Science promise	Mean	4.05	3.99	2.28
	SD	(1.41)	(1.59)	(1.23)
	N	149	149	149
Pro + Politicization	Mean	4.35	4.20	2.07
	SD	(1.52)	(1.57)	(1.23)
	N	128	128	128
Con + Politicization	Mean	3.54	3.47	2.58
	SD	(1.52)	(1.79)	(1.17)
	N	132	132	132
N		1075	1075	1075

Cells present condition means for each dependent variable, with standard errors in parentheses below. Scores for "funding" range from 1 (very strongly oppose) to 7 (very strongly support) US, funding for solar geoengineering research. Scores for "used" range from 1 (extremely unlikely) to 7 (extremely likely) that solar geoengineering approaches will be used to reduce Earth's temperatures in the future. Scores for "anxiety" range from 1 (none at all) to 5 (a great deal) with respect to anxiety respondent feels when thinking about research to study solar geoengineering.

research and perceived that they would be less likely to be used in the future relative to the baseline, the substantive size of the effect is more than halved (**Table 3**, and **Supplementary Tables A6, A7**). In addition, the science benefit frame eliminated the increased anxiety about solar geoengineering research that was elevated by exposure to the *Con frame* in isolation. In short, the context in which the *Con frame* was encountered had a pronounced effect on receptivity to the message.

Colvin et al. (2020, p.25) argue that although public awareness of negative emissions approaches is low, "there are signs of nascent polarization in some fora" (e.g., see Ott, 2018); and, with respect to solar radiation management approaches, "polarization can undermine the capacity for developing a functional discourse and result in debate that is focused on digging into entrenched positions at the expense of seeking solutions" (p.26). Our research question focused on the possible moderating effect of party identification to the randomly assigned experimental treatments (framed messages). To investigate this research question, we estimate OLS regression models with robust standard errors. For each dependent variable, we regress the outcome measure on our condition indicators, omitting the *Control* condition as our reference group, with separate models restricted to respondents identifying as Republican, Independent, and Democrat (**Figure 1**).[7]

Party identification did not modify response to exposure to the randomized treatments across any of the outcome measures.[8] The estimated effect of the experimental condition on support for *funding* solar geoengineering (first column, **Figure 1**) was similar across partisan subgroups, with the *Con frame* exerting a statistically significant reduction in support for all subgroups. The estimated reduction in support is approximately 1-point on the response scale for Republicans and Democrats relative to their counterparts in the *Control condition*. In addition, all subgroups who were exposed to the *Con frame* in the context of science politicization expressed lower levels of support for research on solar geoengineering; however, when the *Con frame* was encountered in a context where the benefits of science was also highlighted, the effect of the frame was weakened or eliminated for all partisan subgroups. The estimated effect of the messages for the other outcome measures also displayed little evidence that they were conditional on partisanship for perceptions that the technology would be used to fight climate change in the future (second column, **Figure 1**), nor did partisanship appear to play a moderating role with respect to reported anxiety about solar geoengineering research across partisan subgroups (third column, **Figure 1**).

DISCUSSION/CONCLUSION

The recommendations from the National Academies of Sciences, Engineering, and Medicine to provide federal funding for further research into solar geoengineering underlines the significance of this as a topic meriting further study as a possible mitigation strategy to combat global climate change. In the absence of sufficient reduction in carbon dioxide emissions to stop the current trajectory of increased concentrations in the atmosphere, it may become necessary to engineer a solution wherein incoming solar energy is re-reflected or filtered. Public opinion will play an important role in determining the feasibility of research into climate engineering and its governance, and therefore, it is crucial to better understand how the public is likely to respond to messages transmitted in mass media about the benefits and risks of emergent

[7]We present the results in a figure containing the plotted point estimates, and error bars representing the 95% confidence interval. We also include the coefficient estimate and associated *p*-value as marker labels to provide additional clarity. The **Supplemental Appendix** (available online) contains the full models corresponding to each dependent variable in a traditional table format **Supplementary Tables A3–A5**.

[8]Our results present models subset by party groups. However, we also estimated additional models using multiplicative interaction terms to test for heterogenous treatment effects across the partisan groups. These global tests for interaction effects are available in the **Supplementary Appendix.**

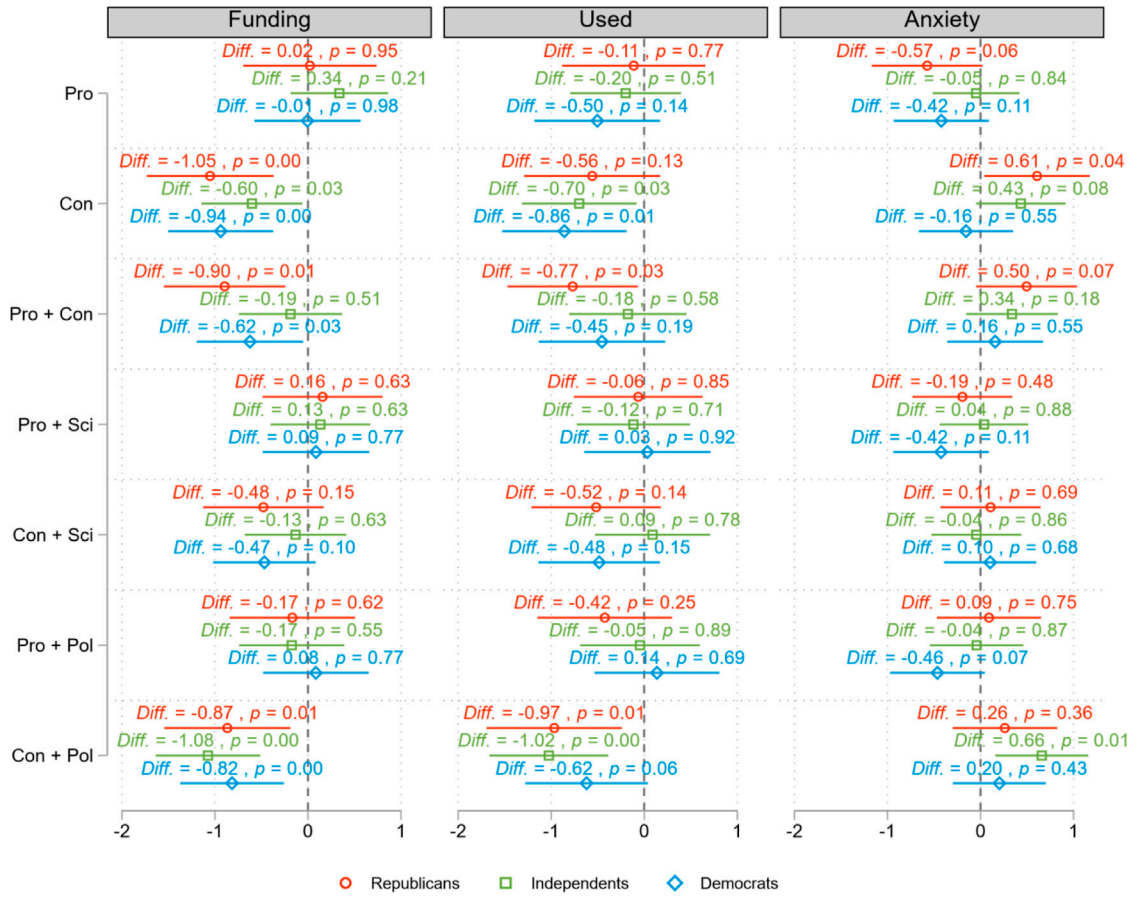

FIGURE 1 | Treatment Effects Across Party Subgroups. Dots are coefficient estimates with error bars representing the 95% confidence interval. Models restricted to Republicans only, Independents only, and Democrats only are colored in red, green, and blue, respectively. All restricted models use co-partisans in the Control group as the reference category. All significance estimates are from two-tailed tests. A complete table of results is available in the Appendix.

technologies with potential applications in the fight against climate change.

Decades of survey research has demonstrated the deep politicization around the topic of "climate change" in the United States. However, our findings show that solar geoengineering is, as yet, a strategy that is unfamiliar to most Americans, and that it also has not yet become politicized. This presents both an opportunity and a challenge. The opportunity will be to take advantage of this lead-time before the issue becomes more central to public discourse to properly frame the issue. The research in this paper suggests that framing will be very influential in shaping the public's attitudes, and that if widespread support for future research on this topic is a desired goal, it will be necessary to carefully frame solar geoengineering in order to avoid some of the issues that have arisen with vaccines or other issues that became controversial and politicized as the public learned more. Colvin et al. (2020) note that it will be important to avoid "ideological bundling" and "conflating" solar geoengineering approaches with other "negative emission technologies" to challenge a dominant narrative of emerging that these approaches are "solely the domain of a particular ideology, political party or social identity" (p.28).

Future research could benefit from population surveys that could also explore the potential importance of prior attitudes and other considerations including how people evaluate or view solar geoengineering as compared with other forms of climate mitigation, attitudes about moral hazard, or general attitudes about the seriousness of anthropogenic climate change. Our research, which was not intended to be a representative survey of the U.S. population but instead a survey experiment on a diverse sample of Americans, suggests that a negative message will sway opinion to oppose research into solar radiation techniques, increase beliefs that it will not be implemented and also increase anxiety about its possible implementation. The effects of the negative message outweigh attempts to counter these arguments with positive information about the

existence of a consensus of scientists recommending its study, the appeal of the technology as relatively inexpensive and a rapid way to address the problem of stabilizing the climate, or appeals about the general benefits of scientific research. Since this topic has such existential importance given the gravity of the issue of climate change, we suggest that further investigation is needed using larger and more representative samples, as well as a focus on populations that might otherwise be more resistant to science when they perceive it to be politicized.

DATA AVAILABILITY STATEMENT

Replication Data for How Negative Frames Can Undermine Public Support for Studying Solar Geoengineering in the U.S., https://doi.org/10.7910/DVN/VUP0TX, Harvard Dataverse.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Georgia State University's IRB.

AUTHOR CONTRIBUTIONS

TB and RP co-designed the study, co-wrote the manuscript, and are equal first authors. JK assisted with data collection and analysis.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.850514/full#supplementary-material

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