How well do people understand the climate impact of individual actions?

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Abstract

Misunderstandings in the relative efficacy of pro-environmental behaviours may have important consequences for climate mitigation efforts. In this study, we evaluate the ability to perceive the carbon footprint associated with individual actions, known as “carbon numeracy”, in 965 members of the North American public using ranking and tradeoff questions. The questions are designed to independently assess the role of knowledge, ability to do tradeoffs, and basic numeracy skills in determining carbon numeracy. We report multiple lines of evidence suggesting that people underestimate greenhouse gas emissions associated with air travel, and to a lesser extent, meat consumption. They are also largely incapable of making tradeoffs between different actions (e.g. the number of hamburgers that would be equivalent to a trans-Atlantic flight in terms of climate impact). Concern for climate change, political orientation and education were not significant predictors of accuracy in making tradeoffs, but basic numeracy was linked with increased accuracy. The results suggest that further education may be necessary to improve carbon numeracy by providing the public with a basic hierarchy of actions according to carbon reduction efficacy. Consumers seeking to balance their carbon budgets may benefit from external aids (e.g. carbon labels associated with actions) to guide emission-related decision making.

1. Introduction

People exhibit greater willingness and intentions to perform pro-environmental behaviours that they believe are more effective in combating climate change (De Boer et al., 2016; Truelove and Parks, 2012). It is therefore important that members of the public can distinguish between actions that are low- or high-impact for mitigating climate change. The most effective actions for reducing an individual's greenhouse gas emissions have been ranked (Gardner and Stern, 2008; Ivanova et al., 2020; Lacroix, 2018; Wynes and Nicholas, 2017), though important questions still remain: Do people understand these rankings? Can they make tradeoffs between different actions? Attempts to improve carbon numeracy are common: Educational curricula instruct students to investigate their own carbon footprints (Wynes and Nicholas, 2019), and researchers communicate the impact of specific actions as components of low-carbon lifestyle interventions (Cornelius et al., 2014). Despite this growing engagement, the "carbon numeracy" of the public is not well understood.

We define carbon numeracy as the ability to correctly understand and manage one's own carbon footprint (or budget). The concept is derived from the ability to manage similar budgets as part of day-to-day living. For example, people manage their bank accounts to balance income and expenses. Many also count calories, using dietary labels to balance their caloric intake against the energy demands of exercise. A person with basic literacy is likely able to identify the most consequential ways they can save money or calories. Someone with greater literacy could also rank different products according to their costs, in the case of financial literacy, and an individual with strong literacy would be able to make tradeoffs between decisions (e.g., skipping X cups of coffee would result in enough savings to purchase a new phone). Those same skills can be applied to management of a personal carbon footprint (e.g., switching to an electric vehicle will reduce emissions more than hang drying laundry).

Past research investigating carbon numeracy has been limited in scale or focused within related domains like energy use or diet. For instance, people have systematic biases against efficiency changes when estimating the impact of behaviours involving household energy use (Attari et al., 2010). Consumers are able to order foods according to relative climate impact, but are unaware of the magnitude of the differences in climate impact between food products (Shi et al., 2016). Consumers tend to underestimate the environmental impact of meat products (Camilleri et al., 2019; Kause et al., 2019; Lazzarini et al., 2016) or car travel (Grinstein et al., 2018). Because of these biases, improved carbon numeracy is believed to be key for individuals to make sustainable choices (Grinstein et al., 2018; Shi et al., 2016). However, little research has examined carbon numeracy across different domains.

Poor carbon numeracy could come from a lack of knowledge, but the translation of knowledge into action is complicated by many factors. These include reliance on “gut feelings” or heuristics (Turrentine and Kurani, 2007) or “moral licensing” (Gifford, 2011) where individuals engaged in pro-environmental behaviours show willingness to forego other pro-environmental behaviours (Truelove et al., 2014). Poor carbon numeracy can also come from limited numeracy skills. For example, people make substantial errors when estimating climate impacts in absolute quantities, as measured in Watts per household activity (Attari et al., 2010) or kilograms of CO_2 per liter of gasoline (Grinstein et al., 2018).

While people are likely to err in estimating the absolute impact of an action, they may still be able to make relative comparisons, like ranking different actions or performing tradeoffs (e.g. “I can do more of X because I already perform Y”, or “I will put more effort into X behavior because it is more important than behaviours Y and Z”). Evidence suggests that some people engage in a type of tradeoff thinking (referred to as “compensatory beliefs”) where they try to balance previous car use by restricting driving in the future, or they realize that certain actions have high climate impacts that are impossible to compensate for with other smaller actions (Hope et al., 2018). One study of compensatory beliefs across seven nations found, for instance, that a cross-national average of 47.6% of respondents believe that a few simple actions to protect the environment is sufficient, while 39.5% agreed that the environmental impact of flying on holiday can be compensated for by reduced car usage (Capstick et al., 2019). A UK study (N=770) on compensatory beliefs found 15.6% of participants agreed that not using a dishwasher can compensate for taking longer showers, 12.2% agreed that composting food can make up for buying imported food, and 3.6% agreed that flying abroad can be made up for by not eating meat (Kaklamanou et al., 2015). The authors suspected that their survey methodology may lead to conservative levels of agreement, suggesting that compensatory thinking is neither very widespread nor so negligible that it should be ignored by those designing education programs or behavioural interventions.

Even individuals who do not actively engage in compensatory thinking but who are still conscious of the impact of their decisions could benefit from greater carbon numeracy. For example, some studies of "food miles" have found that shifting diets can have a greater impact on one's carbon footprint than buying local food (Weber and Matthews, 2008). One UK study found that driving more than 7 km to a local farm shop for vegetables results in higher greenhouse gas reductions than vegetables being delivered by a long-distance, mass distribution system (Coley et al., 2009). In that hypothetical case, an implicit tradeoff is made, but emissions are not reduced because the individual prioritized a low-impact action (purchasing local food) over a high-impact action (driving a personal vehicle).

Understanding public carbon numeracy and its components, such as the ability to perform tradeoffs, is therefore important to education and outreach surrounding pro-environmental behaviours. To assess carbon numeracy, we surveyed members of the North American public through an online survey tool distributed on Amazon Mechanical Turk, as well as undergraduate students at a major North American university. Participants were asked to rank various climate-related behaviours and then to perform tradeoffs between them (comparing air travel with diet, for instance). Results were similar between the two samples (e.g. demographic variables were not significant predictors of tradeoff accuracy) so we combined them in the analysis (separate analyses are available in Online Resource 1). The results provide insight into the factors that predict higher carbon numeracy and the limits of what can be expected even from engaged individuals.

2. Methods

A pilot study with 178 participants was conducted at the University of British Columbia in January 2017 (see Online Resource 2 for methods and results). Following analysis of the pilot results, we revised and expanded the survey and conducted pre-test surveys in spring of 2017, with edits made iteratively following the suggestions of 22 participants. Ethics approval was granted by the UBC Behavioural Research Ethics Board. Surveys were then conducted on the Qualtrics survey platform with North American participants recruited from Amazon Mechanical Turk in June of 2017. Additional surveys were conducted in the 2017-18 academic year (from September 2017 to March 2018) in seven undergraduate classes at the University of British Columbia. A total of 675 students were in attendance at these classes, but participation was optional; 414 of the student surveys were sufficiently complete to be included in data analysis (a completion rate of 61%).

Participants in both groups who failed to answer an attention check question were redirected to the completion message and excluded from the results. The responses of participants were removed from the sample where it was clear that answers were not provided in good faith (for instance, rating every single action as low impact). We also removed participants from the results when they finished the survey in less than five minutes. In total the responses of 55 Mturk participants and 42 UBC students who completed the survey were removed from the data for these reasons.

2.1 Survey design

There were five parts to the survey (see Online Resource 3 for the full survey). First, participants were asked an open-ended question concerning the most effective action they could take to reduce greenhouse gases that contribute to climate change. Second, the participants were asked to categorize 15 actions as low (<1% of a person's carbon footprint), medium (1-5%) or high impact (>5%), following designations from Wynes and Nicholas (2017). Thirteen of the fifteen actions were chosen to represent a range of high-, medium- and low-impact actions. These included "Switch from an SUV to public transit for one year" (high-impact), "Wash your laundry in cold water for one year" (medium-impact) and "Don't litter for one year" (low-impact). Two civic actions were also included to gauge whether participants viewed collective/civic actions as more effective than consumer behaviours ("Vote for a political party that is proposing a carbon tax" and "Vote in favour of a nuclear power plant").

Third, participants were asked to perform four trade-off questions, such as a tradeoff between two household energy saving actions: "Hang drying clothing instead of using a dryer saves electricity, which reduces greenhouse gas emissions. If someone chooses to hang dry one load of laundry, how long can they leave an LED light bulb switched on and still produce the same amount of greenhouse gases as if they had used the dryer? Please give your best guess." The other three tradeoffs were: a year of eating a vegetarian diet versus the amount of time needed to compensate for the same emissions by purchasing food without packaging, kilometers driving a hybrid vehicle compared to 100 kilometers of driving a conventional vehicle, and the quantity of hamburgers needed to equal an economy class ticket on a trans-Atlantic flight.

The tradeoff questions were selected to represent a spectrum of compensatory beliefs; one was between very similar products (a comparison between personal vehicles), two are within the same domain (one comparison within diet and one within household energy) and one crosses domains (diet and transportation). We included cross-domain comparisons because climate change is inherently a cross-domain problem: actions in different domains (e.g., travel, energy, diet) are quantified using the same climate metrics ($kgCO_2e$). Personal carbon footprint analyses and education around individual climate actions implicitly ask people to make cross-domain comparisons. Therefore, the core motivation for these tradeoff questions is to test the ability to compare carbon impacts of different activities.

Fourth, participants were asked two sets of control questions to test whether lack of knowledge, lack of numeracy or environmental biases was a barrier in providing correct answers. In the first set, explicit numeric information was provided, e.g. “We have provided more information to this question. Hang drying clothing instead of using a dryer saves electricity, which reduces greenhouse gas emissions. If someone chooses to hang dry their clothes for one load (thereby saving 3400Wh), how long can they leave an LED light bulb switched on (10W per hour) and still produce the same amount of greenhouse gases as if they had used the dryer? Please give your best guess.” The second set of control questions removed the climate context since biases in favour of environmentally symbolic actions (e.g., driving a hybrid vehicle) may cause biased estimates of the impacts of those actions even when sufficient mathematical information is provided (Sütterlin and Siegrist, 2014). For example, the corresponding question to the above reads: “A scientist finds a very old tree and calculates that it is 3400 years old. How many decades (1 decade = 10 years) has this tree been alive? Please give your best guess.” Participants who answered the non-climate control question correctly but not the first control question were either being misled by their environmental biases or find it more difficult to answer the same mathematical question in a climate context.

Lastly, participants were asked about their concern for climate change, about their estimate of the percentage of climate scientists that believe climate change is mostly caused by humans, and a series of demographic questions. The complete survey as well and calculations used to determine an accurate range of estimates can be found in Online Resource 3 and 4.

2.2 Survey analysis

Responses to the open-ended question on the most effective action that the participant could take to reduce greenhouse gas emissions that contribute to climate change were coded into 25 categories adapted from Wynes and Nicholas (2017). Based on their approach, we separated out the most effective versions of some actions (e.g. eat a plant-based diet, live car free) from less comprehensive versions of the same action (e.g. eat less meat, drive less/more efficiently/carpool etc.). When respondents provided two or more actions that they saw as being the most effective, we only coded the first action described. Some respondents indicated policies that the government could make on their behalf (e.g. "better regulation from government regarding car use"), which we coded as "Government". Others denied the existence of human caused climate change (coded as "Deny climate change") while still others gave tautological responses such as "reduce carbon footprint", coded here as "reduce GHGs". Because of evidence that attitudes about climate change mitigation vary by political ideology (Hornsey et al., 2016), we also grouped the results by political orientation.

Climate concern was measured using a previously tested 4-item scale (α=0.88 in our sample), with the third item reverse-coded (Attari et al., 2010). Numeracy was measured by taking the number of correct responses to the eight control questions: the four questions where participants were provided additional data to answer the estimates correctly, and the four questions where participants were asked to make the exact same calculation process but in an everyday context unrelated to climate change.

To compare accuracy across all four tradeoff questions we calculated the absolute log error (Grinstein et al., 2018) for each tradeoff question and then took the average error of the four tradeoff questions.

$$\text{(1) Absolute Error} = \left|log_{10}\left(\frac{participant\ estimate}{central\ value\ of\ actual\ calculation}\right)\right|$$

For the purpose of using linear regression to understand which demographic variables predict accuracy, absolute values are preferable to estimation bias because, with estimation bias, overestimation in one category (positive sign) would counteract underestimations in another category (negative sign), causing a participant to incorrectly appear more accurate overall. We also calculated, "estimation bias" which uses the same calculation but without taking the absolute value, to test the direction of bias for each of the four tradeoff questions.

$$\text{(2) Estimation Bias} = log_{10}\left(\frac{participant\ estimate}{central\ value\ of\ actual\ calculation}\right)$$

A participant overestimating by a factor of 10 would yield an "estimation bias" of 1, while underestimating by a factor of 10 would yield an estimation bias of -1.

We ran linear regression analyses with demographic data, numeracy and climate score (concern for climate change) as predictor variables and with average absolute log error as a response variable. To test if the outliers present in the data were affecting the results, we removed the outliers and repeated the analysis, finding no difference in outcomes (predictor variables that were significant remained significant and vice-versa). We used logistic regression with repeated cross validation to determine those variables that were significant predictors of choosing a plant-based diet in the open-ended question. These calculations were performed in R Version 3.5.1. Data is available upon request, as permitted by our Behavioural Research Ethics agreement.

Incomplete survey data were handled as follows. In two tradeoff questions participants were asked to provide units. If they provided nonsensical units these were entered as NA values. Also, when performing regression calculations, we preserved the data from responses on the other tradeoff questions by imputing the values for the 39 individuals who failed to make a usable estimate for the vegan tradeoff question and the 125 values for the LED tradeoff question using the k nearest neighbour method (Kowarik and Templ, 2016). This is justifiable since these NA values are unlikely to be completely random. We also performed the regressions using a smaller sample where these individuals were omitted and found no substantial differences in the results (variables that were previously significant predictors remained significant and vice-versa).

2.3 Participant Information

414 students completed the survey. 62% were female, 22% were in their first year, 29% in second year, 27% in third year, 22% in their fourth year or higher. 55% described themselves as liberal (scores of 5-7), 14% as conservative (scores of 1-3) and 31% as moderates.

551 individuals completed the survey on Amazon Mechanical Turk. 53% female, 47 Canadian, with an average age of 37. Median income was $30000-$39000, 91% held high school diplomas or higher and 55% held Bachelor degrees or higher. 57% of the sample described themselves as liberal (scores 5-7), 23% as conservative (scores 1-3) and 20% as moderates.

3. Results

Participants were first asked to describe the most effective action they could take to reduce greenhouse gas emissions (Figure 1). The most frequent response type was actions related to reduced driving or "Drive less" (e.g. carpooling, buying a more efficient vehicle etc.). These had more than twice as many responses as using public transit, biking or walking. Very few participants (12 of 965) listed reducing air travel as the most effective action they could take, despite reducing air travel being one of the highest impact actions among wealthier people (Jones and Kammen, 2011). We did not request income data from students, but of the 550 MTurk respondents, 84 reported incomes of >$80,000 and 12 reported incomes >$150,000. Of the 84 participants with incomes above $80,000, only one selected reducing air travel as the most effective action they could take (four said "Recycle", and 39 said "Drive less"). We separated the results by political orientation; no conservatives described voting as the most effective action and few selected eating a plant-based diet or eating less meat (Online Resource 5). Most responses focused on consumer-oriented activities, with less than 5% of responses categorized as one of four types of political action (vote, raise awareness, join an organization, or contact an elected official).

[Figure 1 about here]

Fig. 1 The 25 most common responses to an open-ended question about the single most effective action the participant could take to reduce greenhouse gases. Color indicates self-reported political orientation. Two individuals with no self-reported political orientation not shown here.

Participants then categorized 15 pre-selected actions as high-, medium- or low-impact in terms of reducing greenhouse gas emissions (Figure 2). Switching from driving an SUV to public transit, which is a high-impact action (Wynes and Nicholas, 2017), dominated in terms of the highest average ranking. The same percentage of our sample ranked eating a vegan diet and switching from plastic to canvas bags as high impact, even though eating a vegan diet is roughly 180 times more effective than switching bag types (Wynes and Nicholas, 2017). The distribution of rankings for a trans-Pacific flight was nearly equivalent to that for littering, despite the fact that a trans-Pacific flight would represent a large fraction of most people's annual carbon footprint whereas littering has no effect on greenhouse gas emissions.

These findings appear to be robust to the choice of method: in the pilot experiment, when a student sample was asked to rank actions from 1-15 (with 1 being most effective) instead of sorting them into high-, medium- or low-impact, they provided rankings that resulted in similar relative orderings. For example, the action "Switch from an SUV to public transit" was, on average, perceived to be the most effective, while buying non-GMO foods was perceived to be the least effective (Online Resource 2).

We further examined individual accuracy by counting the number of times that a participant correctly ranked an action as high-, medium-, or low-impact. Poisson regressions showed that higher ranking accuracy was associated with numeracy and education, but not with age, gender, income, political orientation or concern for the climate.

[Figure 2 about here]

Fig. 2 Proportion of participants that ranked each of the 15 actions as low (dark blue), medium (medium blue) or high impact (light blue). Each action is also labelled at right for the assessed impact based on past research (Wynes and Nicholas, 2017). Actions assessed as low impact account for less than 1% of an average North American's annual carbon footprint, medium impact account for 1-5% and high impact account for more than 5%. Note that not all percentage values add to 100% due to rounding.

After the ranking questions, participants answered four questions, each involving a tradeoff between two actions. For each tradeoff question, participants were asked to estimate how much of one activity would be necessary to achieve the same emissions reductions as the other activity (Table 1). For example, one tradeoff question is how many hamburgers a person would have to give up to offset the emissions from a flight from New York to London (see Online Resource 3 for the questions).

Table 1 about here

Based on estimation bias calculations, we find that participants underestimated the emissions from a flight compared to the emissions from a hamburger, as well as the emissions from drying laundry compared to use of an LED lightbulb, and they severely underestimated the emissions of a vegetarian diet compared to a diet that avoids food packaging (Figure 3). Participants were most successful at answering the hybrid vehicle question, although even with that question, less than one quarter (22.6%) of the responses were accurate. Only one out of 965 participants correctly answered three questions, and no participant made correct estimates for all four questions. The four tradeoff questions taken together do not constitute a valid measure of the carbon numeracy construct (Cronbach's alpha for the Absolute Errors on the four tradeoff questions was 0.14).

[Figure 3 about here]

Fig. 3 a) Distance travelled by a hybrid versus 100 miles in a conventional midsize vehicle (absolute emissions=25-32 $kgCO_2e$). b) Hamburgers versus a Trans-Atlantic flight (absolute emissions=477-907 $kgCO_2e$). c) Hours of operating an LED lightbulb versus hang drying one load of laundry (absolute emissions=1.9 $kgCO_2e$). d) Years of eating food without packaging versus one year of vegetarian diet (absolute emissions=1113 $kgCO_2e$). The red area highlights the correct range of answers. Note that some estimates beyond the range of the x-axes are not visible in each graph.

We further examined basic numeracy by asking the same trade-off questions but with additional numerical information provided as well as by asking trade-off questions with similar mathematical operations but where the climate context was replaced by a more familiar situation (Table 1). Participants were more accurate in answering these control numeracy questions. For instance, for the hybrid vehicle question, 22.6% of the estimates to the original question were accurate, 46.2% were accurate when given the additional numerical information, and 83.2% were accurate for the same numerical questions with the climate context removed ($\chi^2(2)=720.90$, $p<.001$). Chi-squared tests with Bonferroni correction showed that the pairwise differences between the estimates and the controls for all four tradeoff questions were significant (full analysis available in Online Resource 5).

To identify factors determining tradeoff accuracy, we ran hierarchical regressions (Table 2) with the following predictors for the full sample: basic numeracy (the number of correct responses in the control tradeoff questions), rank score (accuracy in ranking the actions as high, moderate, or low-impact), climate score (items measuring concern for climate change), age, gender, and political orientation. We found that only basic numeracy and rank score were significant predictors of tradeoff accuracy (accuracy measured as the absolute value of the estimation bias). Basic numeracy and rank score were weakly correlated ($r_s=0.10$, $p=.001$). Neither age, gender, income, nor education were predictive of tradeoff accuracy (Online Resource 1). Additionally, there was a weak correlation between concern for climate change and tradeoff accuracy ($r_s=-0.08$, $p=.028$) as well as between political orientation and tradeoff accuracy (r_s=-0.08, p=.022), though this relationship was no longer significant when accounting for basic numeracy in the regression models. Correlation between the accuracy on the four tradeoff questions was low (highest correlation of r=0.10, p=.005 between hybrid and flight tradeoff accuracy).

Table 2 about here

4. Discussion

Individual climate action is receiving increasing attention in the media and in public education. But motivated individuals will waste time and effort focusing on marginally effective actions if they hold substantial misperceptions about the climate impact of those actions. It is therefore important to understand which actions the public perceives as more effective and whether individuals have the skills that are necessary to estimate and manage their own carbon footprint. These results indicate that the public err substantially in their estimations of the climate impact of individual actions. Below we discuss three key implications of these findings. First, people correctly understand the impacts of personal vehicle use, but underestimate and overestimate the impacts of behaviours like littering and air travel. Second, we show that aspects of carbon numeracy, like tradeoffs, are inherently difficult, and discuss reasons for this difficulty. Last, there are few characteristics that predict increased accuracy in tradeoffs, suggesting a limited suite of options for improving higher-level carbon numeracy.

4.1 Notable underestimations

Consistent with previous research (Truelove and Parks, 2012), we find that individuals correctly comprehend the climate impacts of personal vehicle use, but overestimate the impacts of behaviours like littering or using reusable grocery bags. Judgments may be led astray by the availability heuristic in such cases: individuals underestimate the impacts of clothes dryers compared to LED lightbulbs (Attari et al., 2010), perhaps because household lighting is cognitively available. In the case of personal vehicle use, frequent communication from authorities on this topic (Wynes and Nicholas, 2017) may have resulted in the strong connection between cars and greenhouse gas emissions.

We find robust evidence that people underestimate the climate impact of air travel. Very few participants (1%) mentioned it in the open-ended question as the most effective action they could take even though flying frequently occupies a large proportion of many people's carbon footprints (such as those with high incomes) (Lacroix, 2018). Participants were more likely to rank recycling or switching from plastic to canvas bags for one year as more effective actions than avoiding one trans-Pacific flight. The evidence from the tradeoff question on air travel is less conclusive. The poor estimation on the air travel and hamburger tradeoff question could have come from participants underestimating the emissions associated with flying, or from overestimating the emissions associated with hamburgers. However, the emissions from meat consumption was shown to be underestimated in two other items (Figure 2 and Figure 3). One possible explanation then is that participants underestimated the climate impact of meat consumption but underestimated the climate impact of the air travel to an even greater extent.

Underestimating the emissions of air travel may be especially problematic; in a recent survey of 673 Swedes who had given up or drastically reduced their air travel, individuals frequently credited a realization that flying occupied a large proportion of their "climate budget" as a motivator for reductions (Söderberg and Wormbs, 2019). Policymakers implementing carbon labels on airline tickets might therefore consider using cross-domain comparisons to illustrate the full impact of flying, rather than providing a quantity of emissions without context. Similar labels that reported greenhouse gas quantities in terms of "lightbulb minutes" were tested as carbon labels on soup cans and found to reduce purchases of the beef soup product (Camilleri et al., 2019).

Underestimations of air travel and meat consumption are consistent with a lack of focus on these actions in expert communications. For example, driving and recycling are mentioned more frequently in science textbooks and government documents (Wynes and Nicholas, 2017) and were more common as well here in the responses to the open-ended question. Our participants were more educated and more liberal than a representative sample of North Americans so the limitations in their carbon numeracy suggest that the population at large would have even less success at assessing the impact of their behavior on emissions. People overestimated the climate impact of well-known actions like recycling and switching to canvas bags, possibly due to conflation of pro-environmental and pro-climate actions.

The findings of the ranking question are somewhat limited. Because the survey required allocating behaviours into low-, moderate-, and high-impact categories, participants may have exhibited "partition dependence", a phenomenon where people tend to allocate equally between categories. The effect persists even when participants are told that the categories are arbitrary but is substantially reduced by expertise (Fox et al., 2005). This effect therefore would not explain 17% of our sample selecting littering as high-impact when it has zero climate impact, but might very well explain why so many individuals ranked a low-impact action like buying local food as moderate impact (40%). The broader finding that some actions (like recycling) are over-estimated, while other actions (like meat consumption and air travel) are underestimated, was confirmed through a different approach not subject to partition bias, where participants in a separate sample (n=178) were asked to rank actions from 1-15, rather than sort actions into low-, medium- and high-impact categories (Online Resource 2).

4.2 Understanding tradeoffs

Participants showed less success in making tradeoffs than in ranking different actions. These limitations may be due to a general lack of numeracy (shown in linear regressions), lack of climate knowledge (participants performed 56% better on tradeoff questions once given the requisite starting values), motivated reasoning (Sütterlin and Siegrist, 2014), or the inherent difficulties of the climate context (participants scored 22% better on the non-climate numeracy control questions). There are also inherent limitations to determining one's carbon footprint. Other budgeting activities undertaken by the public, like calories or bank balances, involve values with higher certainty. Even with expert knowledge, there remain large uncertainties in the warming effects of meat production and air travel. Researchers have called for better education of consumers to improve carbon numeracy (Grinstein et al., 2018; Shi et al., 2018), and there is evidence of successful interventions in related fields. For instance, providing simple heuristics about household energy use can lead to better understanding in that domain (Marghetis et al., 2019). Further research into the potential of such heuristics for solving misperceptions of people's own carbon footprints would therefore be beneficial.

4.3 Limitations

Our intention with this research was not to define a measurable construct for carbon numeracy - the concept of numeracy by itself is a highly contested topic (Coben et al., 2003). Instead we sought to identify strengths and weaknesses in the public's ability to manage a carbon footprint that would affect their decision making. Still our research provides a first step for others who would seek to define a measurable construct. Because individuals were overwhelmingly ill-equipped to answer tradeoff questions, agreement among the four tradeoff questions was very low. Researchers seeking to identify a robust measurement may benefit by using more straightforward questions, such as ranking the impact of a variety of actions or products, or using tradeoffs that are more intuitive and within domains. Limiting tradeoff questions to those within domain would also have the benefit of being more generalizable, since people are more likely to conceptualize tradeoffs in this way (Hope et al., 2018).

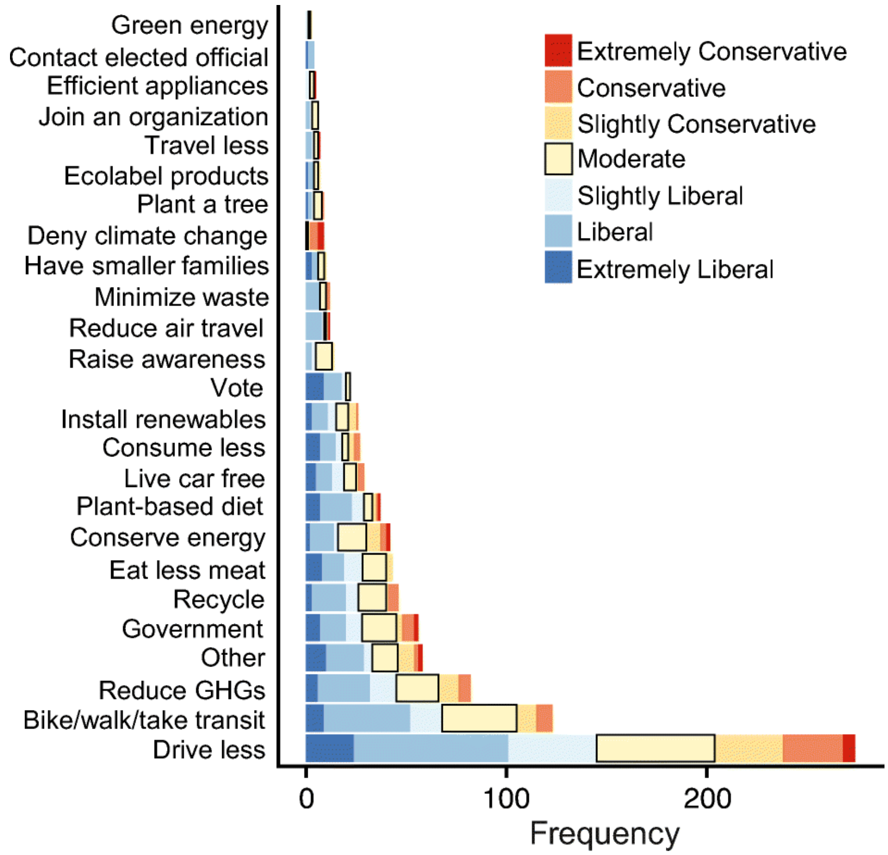
Future research that makes use of tradeoff questions could also consider directionality. We intentionally phrased tradeoff questions to avoid anchoring as much as possible, which explains the direction of some tradeoffs (e.g. we asked how many hamburgers are equivalent to one flight instead of how many flights are equivalent to one hamburger). Still, others could explore the robustness of these results by reversing the comparisons, e.g. "What distance could you fly while being responsible for the same emissions as are created from producing a single hamburger?"

4.4 Implications

Communicators and policymakers need to understand how members of the public perceive the climate impacts of their decisions. For instance, participants in our study consistently showed an understanding that personal vehicle use is a high-impact activity, and also showed some ability to perform tradeoffs in that domain. Based on this relatively strong understanding of personal vehicles, journalists and politicians may be justified in continuing to compare the magnitude of climate policies to the number of cars taken off the road, rather than making a comparison to other domains where the public routinely over or underestimates emissions.

Regarding those individuals who are motivated to monitor their own carbon footprint, our study may have identified an upper bound of potential competence. Unlike in past research where concern for climate change was associated with superior understanding of energy use (Attari et al., 2010), only numeracy and ability to rank actions was found to predict accuracy in tradeoff questions. Climate impacts are perhaps more complicated than personal finances, calories or energy use; they cross domains, involve understanding of not just electrical energy, but also agricultural intensity and fuel efficiency. The only tradeoff that participants managed with relative success (the hybrid vehicle question) was one that already demands day to day numeracy on the topic, is readily available cognitively, and did not involve multiple domains.

While education is still necessary to correct larger misperceptions (especially regarding air travel and meat consumption) and to provide the public with a basic hierarchy of action efficacy, consumers who want to maintain a low carbon footprint would be best served by carbon labels in intuitive displays at the point of purchase, or by a price on carbon, because they are likely incapable of successfully balancing their own carbon footprints.


Green energy
Contact elected official
Efficient appliances
Join an organization
Travel less
Ecolabel products
Plant a tree
Deny climate change
Have smaller families
Minimize waste
Reduce air travel
Raise awareness
Vote
Install renewables
Consume less
Live car free
Plant-based diet
Conserve energy
Eat less meat
Recycle
Government
Other
Reduce GHGs
Bike/walk/take transit
Drive less
Extremely Conservative
Conservative
Slightly Conservative
Moderate
Slightly Liberal
Liberal
Extremely Liberal
0
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Frequency

Figure 1

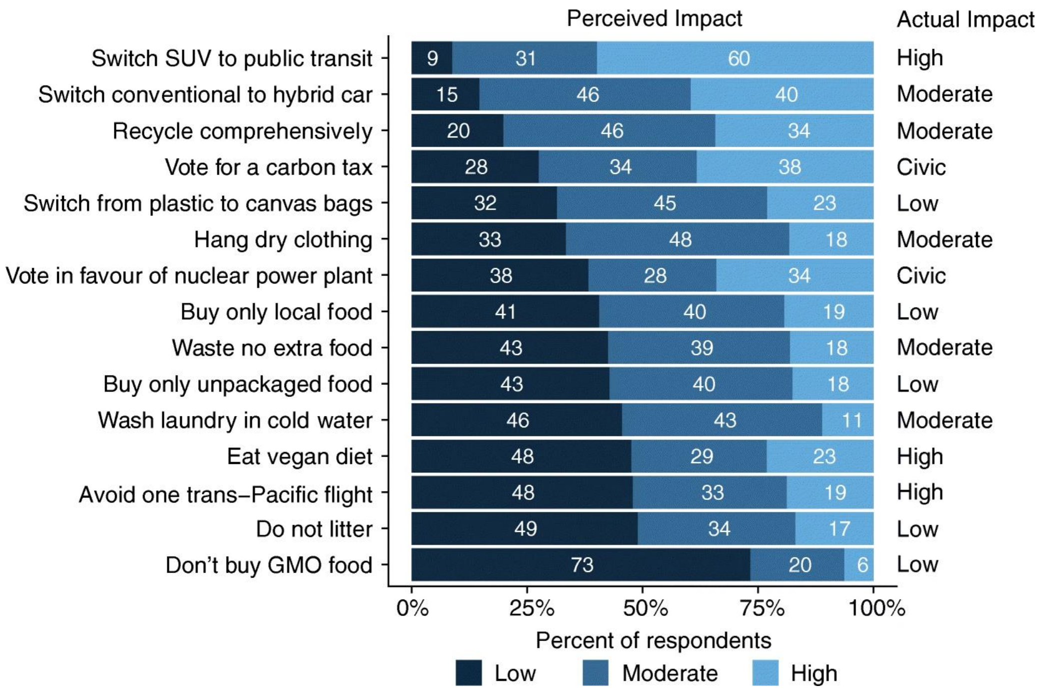
Perceived Impact
Actual Impact
Switch SUV to public transit
9
31
60
High
Switch conventional to hybrid car
15
46
40
Moderate
Recycle comprehensively
20
46
34
Moderate
Vote for a carbon tax
28
34
38
Civic
Switch from plastic to canvas bags
32
45
23
Low
Hang dry clothing
33
48
18
Moderate
Vote in favour of nuclear power plant
38
28
34
Civic
Buy only local food
41
40
19
Low
Waste no extra food
43
39
18
Moderate
Buy only unpackaged food
43
40
18
Low
Wash laundry in cold water
46
43
11
Moderate
Eat vegan diet
48
29
23
High
Avoid one trans–Pacific flight
48
33
19
High
Do not litter
49
34
17
Low
Don't buy GMO food
73
20
6
Low
0%
25%
50%
75%
100%
Percent of respondents
Low
Moderate
High

Figure 2

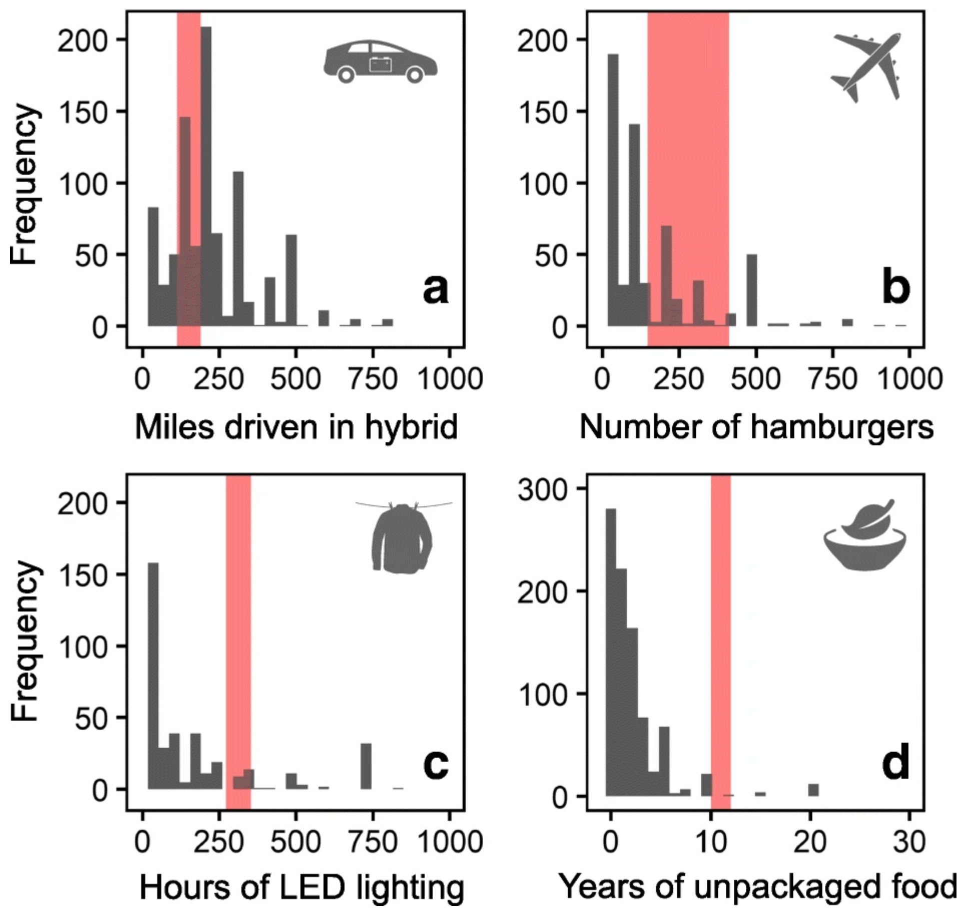
Frequency
Miles driven in hybrid
Number of hamburgers
Hours of LED lighting
Years of unpackaged food
a
b
c
d

Figure 3

Table 1: Accuracy in making the four climate impact tradeoffs

Tradeoff Question	Correct range	Median estimate	Percent of correct answers			Estimation bias [95% CI] (see methods)
			Tradeoff question	Additional information provided	Non-climate control question	
Miles of driving hybrid vs 100 miles in conventional car	112-190 miles	200 miles	22.6%	46.2%	83.2%	0.13 [0.10,0.16]
Numbers of hamburgers vs one trans-Atlantic flight	146-410 burgers	100 burgers	17.4%	82.6%	95.5%	-0.21 [-0.28,-0.14]
Hours of LED usage vs one load of hang-dried laundry	272-354 hours	60 hours	2.6%	71.0%	91.0%	-0.45 [-0.54,-0.35]
Years of unpackaged food vs one year vegetarian food	10-12 years	1.1 years	2.6%	68.2%	85.1%	-0.98 [-1.03,-0.92]

Table 2: Hierarchical regression for tradeoff accuracy (average error) on four tradeoff questions

Model	(1)	(2)	(3)	(4)	(5)	(6)
Basic numeracy	-0.04***	-0.03***	-0.03***	-0.03***	-0.03***	-0.03***
	(-0.05, -0.03)	(-0.04, -0.02)	(-0.04, -0.02)	(-0.04, -0.02)	(-0.04, -0.02)	(-0.04, -0.02)
Rank score		-0.03***	-0.03***	-0.03***	-0.03***	-0.03***
		(-0.04, -0.02)	(-0.04, -0.02)	(-0.04, -0.02)	(-0.04, -0.02)	(-0.04, -0.02)
Climate score			-0.002	-0.003	-0.002	-0.001
			(-0.01, 0.001)	(-0.01, 0.001)	(-0.01, 0.001)	(-0.01, 0.003)
Age				0.001	0.001	0.001
				(-0.001, 0.002)	(-0.0005, 0.002)	(-0.0005, 0.002)
Gender					0.01	0.01
(Female)					(-0.02, 0.05)	(-0.02, 0.05)
Political orientation						-0.01
(1=Extremely liberal, 7=Extremely conservative)						(-0.02, 0.01)
Observations†	965	965	965	965	957	955
R^2	0.04	0.06	0.06	0.06	0.06	0.06
Adjusted R^2	0.04	0.06	0.06	0.06	0.05	0.05

Note: 90% confidence intervals in parentheses. *p<.1, **p<0.05, ***p<0.01
†Models 5 and 6 have fewer observations due to the removal of eight participants who selected gender responses other than male or female and two participants who did not select political orientation

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