Neural Correlates of Attitudes and Risk Perception for Food Technology Topics[1]

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ABSTRACT

Food technologies provide numerous benefits to society and are extensively vetted for safety. However, many technological innovations still face high levels of skepticism from consumers. To promote development and use of food technologies, it is critical to understand the underlying causes of consumer acceptability concerns. The current study uses a neuroscience-based approach to understand consumer attitudes and perceptions of risk associated with food technologies and investigate how such attitudes impact consumer's processing of information related to food technologies. We used functional magnetic resonance imaging (fMRI) to measure brain activation while participants processed infographics related to food technology topics. For technology topics perceived as riskier (antibiotics and hormones), activation was higher in areas of the lateral prefrontal cortex ($P < .001$) that are associated with decisional uncertainty. In contrast, technology topics that were viewed more favorably (sustainability and animal welfare) tended to activate the ventromedial prefrontal cortex ($P = .049$), a region that processes positive affect and subjective value. Moreover, for information about hormones, the lateral PFC activation was associated with individual differences in resistance to change in risk perception ($P = .01$). These results reveal how attitudes and risk perception relate to how the brain processes information about food technologies and how people respond to information about such technologies.

Key words: food technology, human subjects, risk perception, fMRI, prefrontal cortex, attitudes

INTRODUCTION

Innovations in food technology hold great promise for improving food quality, availability, safety, and sustainability. However, like other technological innovations (Kleijnen et al., 2009), new food technologies are often met with resistance in the marketplace. Consumers tend to be neophobic when it comes to foods (Pliner and Hobden, 1992), particularly foods produced with new technologies (Cox and Evans, 2008), even when expert scientists have vetted the technologies for safety (Hansen et al., 2003). Such neophobia presents a barrier to development of novel technologies as well as their adoption by food producers. The high cost of investment in bringing technologies to market or deploying such technologies in food production can become financially risky when faced with the high potential for rejection by consumers (Lusk et al., 2014). Thus, to promote development of safe, effective technologies for improving food sustainability and safety, it is critical to understand the causes of consumer resistance to technological innovation.

Consumer research on food technologies has uncovered several factors that influence acceptance and resistance to innovation, as well as people's willingness-to-pay for such innovations in the marketplace (Lusk et al., 2014). At a proximal level, people's attitudes and perceptions of risk play a critical role in influencing acceptance of new food technologies. Compared to organic or "natural" foods, foods produced with technologies are often viewed as having lower benefits and higher risks (Frewer et al., 1994; Saba et al., 2000). Thus, consumers are often willing to pay more to avoid technologies such as genetically modified organisms (GMOs), hormones, or antibiotics than they are to purchase food created with them (Lusk et al., 2015; Lusk et al., 2014; Roosen et al., 2015). The origins of consumers' less positive attitudes and heightened risk perception to food technologies remain elusive, but factors that are known to

play a role are the perceived naturalness of foods or a technology (Tenbült et al., 2005; Siegrist, 2008), tendencies to overweight low probability risks (Slovic, 2016), perceived controllability of exposure (Siegrist et al., 2008), familiarity (Tenbült et al., 2008), trust in science (Lang and Hallman, 2005; Siegrist et al., 2007), and personal ethical beliefs (Sparks et al., 1995).

More recently, research on food technology has begun to turn to neuroscience techniques to understand the cognitive mechanisms that give rise to consumer acceptance of food technology at a finer-grained level (Bruce et al., 2014; Lusk et al., 2015). Neuroscience research on food technologies follows the recent focus in behavioral economics on “neuroeconomic” approaches that have proven useful for understanding a number of basic economic phenomena, such as loss-aversion (Rick, 2011), temporal discounting (Kable and Glimcher, 2007; Ballard and Knutson, 2009), and how uncertainty influences preferences and perceptions of value (Platt and Huettel, 2008; Rushworth and Behrens, 2008). Multiple brain systems track basic behavioral economic constructs like value and risk including “hot” affective systems that tend to be governed by more automatic, affective information, and “cool” systems that promote more deliberate, rational decision making (Bechara et al., 2000; Goel and Dolan, 2003; McClure et al., 2004).

Much of neuroeconomic research has focused on the prefrontal cortex (PFC) as critical for value-based decision making processes. The prefrontal cortex is part of the frontal lobe and governs much of our “higher-level” cognitive functions such as planning and reasoning, as well as numerous social and affective processes. In terms of its role in value-based decision making, there are key differences within the prefrontal cortex between the lateral PFC (on the sides of the brain) and the medial PFC (the middle part of the brain, behind the forehead and above the eyes). The lateral PFC tends to track measures of economic risk and uncertainty, which are related to

variability in possible outcomes associated with a decision (Kahnt et al., 2011; Schonberg et al., 2011). It typically activates more when a variety of different outcomes are possible and less when an outcome is completely predictable. The lateral PFC also tends to track individual differences in risk aversion, or people's tendency to overvalue sure bets (Christopoulos et al., 2009). On a mechanistic level, the lateral PFC is thought to be critical for resolving conflicting information (e.g., outcome variability) in cases of higher uncertainty due to its more general role as a center for cognitive control (Miller, 2000; Koechlin et al., 2003; Badre and D'Esposito, 2009).

In contrast to the lateral PFC, the medial PFC, particularly the ventral part of it (the lower side; ventromedial PFC), tends to track the overall subjective value of a decision (Levy and Glimcher, 2012; Bartra et al., 2013). When a decision has high subjective value, this brain region tends to activate more, and when there is low subjective value, it activates less. The medial PFC tracks individual differences in preference for immediate reward (Kable & Glimcher, 2007) as well as individual differences in sensitivity to gains versus losses (Tom et al., 2007). Whereas the lateral PFC is often depicted as a "cold" rational part of the brain, the medial part is often depicted as part of the "hot" affective or emotional part of the brain due to its sensitivity to immediate reward (McClure et al., 2004; Krain, et al., 2006). However, both are sensitive to cognitive and affective information. The lateral PFC is involved in basic regulation of cravings and emotional responses (Delgado et al. 2008; Kober et al., 2010; Kahathuduwa et al., 2016, 2018). Likewise, the ventromedial PFC integrates cognitive and more visceral affective information when computing a subjective value (Roy et al., 2012). For example, the ventromedial PFC tracks people's tendency to rate wines as more subjectively valuable when

they are associated with a higher price tag than when the equivalent wine is low priced ("price placebo effect"; Plassmann et al., 2008; Plassmann & Weber, 2015).

Following general neuroeconomic research, fMRI research on the neurobiological underpinnings of food technology choice has focused on how the PFC engages when making willingness-to-pay judgments. Consistent with the role of the lateral PFC in resolving uncertainty and conflict, lateral PFC has been found to be more active when participants are considering multi-attribute food choices that require them to consider both price and technology attributes (e.g., the price of milk and that it was produced from cloned cows; Lusk et al., 2015), and when participants opt for a higher-priced organic food to avoid a technology (Linder et al., 2010; Lusk et al., 2015). Likewise, activation in the lateral PFC tends to track relevant individual differences that contribute to price-technology conflicts, such as trait-level food technology neophobia (Bruce et al., 2014) and how much people adjust their willingness-to-pay judgments based on advertising (McFadden et al., 2015). In contrast, the ventromedial PFC has been found to be more associated with people's final willingness-to-pay decisions in price-technology trade-offs (Crespi et al., 2015), consistent with its role in computing subjective value. In some cases, such signals from the PFC have been shown to contribute above and beyond many well-established demographic and individual difference contributors to willingness-to-pay, leading to the conclusion that functional neuroimaging provides incremental value in predicting and understanding consumer choices regarding food technology tradeoffs (Lusk et al., 2015).

With the relatively limited neuroscience research on how people perceive food technologies, there are many open questions about how the brain processes information about food technology and how these processes influence potential consumer behavior. Given the critical role that information and education about technologies plays in consumer acceptance,

one important question is how the brain processes information about food technologies and how this processing relates to perceived risk and consumer attitudes. Perceived risk and attitudes are key pre-decisional factors that influence not only how consumers will behave when given a choice between foods produced with new technologies or more “natural” foods, but also how receptive they will be to new information (Sears and Freedman, 1967; Smith et al., 2008; Hart et al., 2009).

In the present study, we scanned individuals while they were processing infographics explaining risks and benefits of six food technology topics: hormones, antibiotics, vaccines, GMOs, animal welfare technologies, and sustainability technologies (see Supplemental Figures). These topics were predicted to vary in terms of perceived risk and attitudes, thus allowing us to examine how risk perception and attitudes relate to and follow from processing information about food technologies. Specifically, hormones and antibiotics were expected to be perceived as most risky and lowest in terms of attitudes, GMOs and vaccines as intermediate, and animal welfare and sustainability technologies were expected to be perceived as generally lower risk and associated with more positive attitudes.

In terms of the brain, we expected that the same basic lateral and medial PFC regions that are involved with processing decisional information in willingness-to-pay judgments would be associated with processing risk and attitude information in the infographics. Indeed, although risk perception is critically different from the outcome uncertainty that is generally thought to underlie the lateral PFC’s contribution to decision making (Schonberg et al., 2011), we hypothesized that the lateral PFC would track perceptions of risk when confronted with infographics viewed as riskier due to uncertainty arising from the conflict between the reader’s risk perceptions and the positive information presented in the infographics. Likewise, we

predicted that general positive attitudes toward the technologies would be associated with more ventromedial PFC activation during infographic processing. This prediction follows from the ventromedial PFC's role in tracking subjective value and positive affective information even outside of choice contexts (Roy et al., 2012).

In addition to our primary goals, which are to examine how risk perception and positive attitudes relate to brain activation, we also examine how individual differences in risk perception and attitude change (from pre- to post-infographic) are associated with individual differences in brain activation. These individual difference effects can augment the primary associations by answering whether, for example, the hypothesized risk-related processing in lateral PFC is generally associated with improving risk perception and attitudes or if it is associated with resisting such change.

MATERIALS AND METHODS

Participants

Fifty-three participants completed the fMRI study. Participants were paid $25 and given an extra $5 for a willingness-to-pay auction that was administered after the fMRI scans. An additional 394 participants completed online versions of the questionnaires without infographics to provide normative data for the pre- and post-questionnaires that are used to measure attitudes and attitude change for the imaging study. These participants were recruited through Amazon's Mechanical Turk and paid $4 for participation. All protocols were approved by the Human Rights Protection Program (HRPP) of Texas Tech University (Proposal number: IRB2018-730; Approved: 9/6/2018).

Behavioral Protocol

The behavioral protocol included pre-scan demographics, attitudes, and buying behavior surveys; scanned infographics exposure, attitudes surveys, willingness-to-pay judgments; and a post-scan survey on more general technology and food attitudes. The pre-scan demographics survey asked people to report their age, sex, ethnicity, first language learned, ZIP code in which they spent the majority of childhood, highest level of education completed, political orientation, and household income. The pre-scan attitudes and behavior survey asked about organic buying behavior, whether they eat meat, and whether they subscribe to any dietary philosophies (vegan, vegetarian, etc.; see Table 1).

The pre-scan attitudes survey contained brief sections on six food technology topics: antibiotics, vaccines, hormones, GMOs, sustainability, and animal welfare. Each section contained two questions each on familiarity, subjective norms, trust in science (their beliefs that scientists understand the risks of the technology), past behavior with the technology (consuming or avoiding food produced with the technology), and perceived control (whether they were able to control their exposure to the food; see Supplemental Table 1). After the pre-scan attitudes survey participants were given brief instructions on how to complete the task inside the scanner.

For the scanned infographics exposure and attitudes surveys, infographics depicting the six food technology topics (antibiotics, vaccines, hormones, GMOs, sustainability, and animal welfare) were presented to participants separately in different scanning runs. The order of infographics was balanced across participants using a Latin square. Within a run, participants were presented with an infographic depicting one of the technologies three times. During each presentation, participants were asked to either focus on attitudinal information (labeled as “attitudes” and “benefits”) or risks associated with the technologies. A brief cue (2 seconds) would tell them prior to each presentation of an infographic which aspect they were to focus on

(risk, attitudes, or benefits), the order of which was randomized within each block for each participant. This was separated by variable duration fixation cross (2, 3, or 4s), which participants were simply told to keep their eyes on while awaiting infographics. The fixation cross provides a baseline that helps to statistically isolate the responses to the different task components. After fixation, the infographic was presented for 30s. After the infographic was presented, fixation was briefly presented (5, 6, or 7 seconds) and then six Likert-type questions about risks or attitudinal information (attitudes or benefits) were presented for 4 seconds each. During these questions, participants keyed in their responses on a sliding scale that ranged from 1 (*strongly disagree*) to 5 (*strongly agree*) by using an MR-safe button box held in their right hand. Finally, the risk and attitudes questions were also separated by fixation, which averaged 4 seconds and was drawn from a truncated exponential distribution. A second and third infographic cue, infographic presentation, and question period would then begin until all questions were answered for an infographic.

After the primary infographic runs, participants completed willingness-to-pay judgments and a set of additional post-scan surveys that are beyond the focus of the present study.

Image Acquisition

Imaging data were acquired at Texas Tech Neuroimaging Institute on a 3T Siemens Skyra using a 20-channel head-coil. Functional images were acquired in the axial plane using the Siemen's product EPI sequence: TR = 2.09 s; TE = 25 ms; θ = 70°; FoV= 192 x 192 mm; matrix = 64 x 64; number of slices = 41, slice thickness = 2.5 mm; 0.5 mm gap. Slices were tilted to reduce orbitofrontal dropout (Deichmann et al., 2003). In addition, a high-resolution anatomical image was collected for each of the participants using an MPRAGE sequence acquired in the sagittal plane: TR = 1.9 s; TE = 2.49 ms; θ = 9°; FoV = 240 x 240 mm; matrix = 256 x 256 mm;

slice thickness = 0.9 mm, slices = 192.

fMRI Analysis

FMRI analysis was conducted using a standard three-level general linear model (GLM) implemented in FEAT (FMRI Expert Analysis Tool) Version 6.00, part of FSL (FMRIB's Software Library, www.fmrib.ox.ac.uk/fsl). Data were first pre-processed using rigid-body motion correction and skull stripping. The first-level model included explanatory variables (EVs) for cue presentation, infographic presentation (separate EVs for risk and attitudes prompts), stimulus presentation for risk and attitudes questions, and participants' ratings as a parametric modulator of the rating questions. First-level models also included nuisance regressors for motion (6 motion parameters and their temporal derivatives) and regressors to "scrub" (censor) volumes with framewise displacement > .9mm (Siegel et al., 2014). The first level model also included temporal derivatives for each task variable, high-pass filtering, spatial smoothing (6mm FWHM), two-stage registration to high resolution anatomical and standard space, and pre-whitening to account for temporal autocorrelation. Second level models included EVs for each infographic type (antibiotics, vaccines, hormones, GMOs, sustainability, and animal welfare). Second-level contrasts included contrasts for each infographic type and two contrasts weighting each infographic type by the average risk / attitude rating (z-scored to ensure contrast weights summed to zero). Third-level models included models for risks and attitudes examining the overall mean infographic effects within subjects, as well as models examining how participant-level changes in infographic specific risk/attitudes impacted activation for those infographics. The threshold for statistical maps were set at z = 3.1 (p = .001, one-tailed) and corrected for multiple comparisons using a cluster-extent threshold based on Gaussian Random Field Theory.

RESULTS

Behavioral Results

Topic differences in average risk perception and attitudes. Our primary question for the behavioral data was how attitudes and risk perception varied between the food technology topics. For risk perception, linear mixed-effects models revealed significant variability between infographics in both pre- and post-infographic exposure conditions [pre: $F(5, 260) = 8.84$, $p < .001$; post: $F(5, 260) = 11.76$, $p < .001$; see Figure 2A]. The overall pattern for both pre and post data was that hormones and antibiotics were viewed as more risky relative to both GMOs and vaccines [pre: $t(52) = 4.64$, $p < .001$; post: $t(52) = 5.07$, $p < .001$], as well as animal welfare and sustainability technology [pre: $t(52) = 4.69$, $p < .001$; post: $t(52) = 6.60$, $p < .001$]. However, GMOs and vaccines were not viewed as more risky than animal welfare or sustainability technology [pre: $t(52) = 1.06$, $p = .29$; post: $t(52) = 0.93$, $p = .35$].

The attitude results were consistent with the risk perception results, however the attitude measures showed larger differences amongst the technologies viewed as less risky (vaccines and GMOs) and the sustainability and welfare topics. There again was significant variability between the food technology topics [pre: $F(5, 260) = 24.81$, $p < .001$; post: $F(5, 260) = 25.75$, $p < .001$; see Figure 2B for post results]. Hormones and antibiotics were associated with less positive attitudes than both GMOs and vaccines [pre: $t(52) = 5.93$, $p < .001$; post: $t(52) = 8.35$, $p < .001$] as well as animal welfare and sustainability technology [$t(52) = 9.07$, $p < .001$; post: $t(52) = 7.65$, $p < .001$]. GMOs and vaccines were also associated with less positive attitudes than animal welfare and sustainability technologies for the pre-infographic survey, $t(52) = 4.36$, $p < .001$, but not the post-infographic survey, $t(52) = 0.33$, $p = .74$.

Risk and attitude change. To assess whether the infographics had an overall positive effect on attitudes and risk perception relative to the pre-infographics ratings, we standardized

the pre- and post-infographic ratings using the means and standard deviations of the normative online sample. This standardization was done to neutralize mean differences between the pre- and post-infographic ratings that are simply due to using different questions (see Supplemental Table 1). Comparing these standardized pre- and post-scores, we found that all topics showed reduced risk perception [hormones: $t(52) = 3.10$, $p = .003$; antibiotics: $t(52) = 3.11$, $p = .003$; GMOs: $t(52) = 2.55$, $p = .01$; vaccines: $t(52) = 6.44$, $p < .001$; animal welfare: $t(52) = 4.13$, $p < .001$; sustainability: $t(52) = 2.41$, $p = .02$] and higher attitudes [hormones: $t(52) = 3.77$, $p < .001$; antibiotics: $t(52) = 3.63$, $p < .001$; GMOs: $t(52) = 4.92$, $p < .001$; vaccines: $t(52) = 5.24$, $p < .001$; animal welfare: $t(52) = 3.10$, $p < .003$; sustainability: $t(52) = 2.78$, $p = .008$] after being exposed to the infographics (post-infographic).

Between Infographic Differences in Activation

Our primary question was how the observed differences in risk and attitudes related to activation during people's processing of the infographics. To test how activation tracked risk and attitudes, we regressed activation during risk and attitude processing blocks on the average risk and attitude ratings for the different infographics. This allows us to test which brain regions track perceived risk during risk-related processing of infographics, and which regions track positive attitudes during general attitude and benefit processing of infographics.

Activation related to risk processing. Four clusters of activation were positively associated with mean risk ratings across infographics (greater activation for higher risk; Figure 3; Table 2): one spanning the left dorsolateral prefrontal cortex (PFC) and left inferior frontal gyrus (IFG; $P < .001$), bilateral superior parietal lobe (left: $P = .002$; right: $P = .040$), and one in the superior and middle temporal gyrus around the temporo-parietal junction ($P < .001$). The lateral PFC was predicted *a priori* given this region's role in processing of uncertainty in decision

making (Kahnt et al., 2011; Schonberg et al., 2011). We hypothesized that this region would be engaged more for higher perceived risk technologies because of the greater uncertainty participants would have when processing positive information about the technologies they perceive as risky. To further illustrate how activation in the lateral PFC varied between the infographics, we extracted mean risk and attitude activation from each subject and plotted them along with the whole-brain results in Figure 3. Note that, because these results are from a region already showing significant tracking of between-infographic risk, it is not appropriate to run additional statistical tests on them (Kriegeskorte et al., 2009); however, the graph is useful to visualize how the lateral PFC is tracking risk. The graph shows that lateral PFC activation tends to be highest for the high perceived risk topics (antibiotics and hormones), but there is less differentiation between the lower perceived risk topics (GMOs, vaccines, animal welfare, and sustainability). Interestingly, as the figure illustrates, the profile of activation across the infographics was mirrored during attitude processing, suggesting that, in this case, the perceived riskiness of the technologies is contributing to activation both when participants are processing risk information and when they are processing more general attitudinal information and benefits.

The other brain regions observed in the temporal and parietal cortex all participate, along with the lateral PFC, in broader attention and cognitive control networks that tend to be more active during cognitively demanding tasks (Corbetta and Shulman, 2002; Spreng et al., 2013). The deployment of more cognitive resources when considering risky technologies is consistent with our overall hypothesis that participants would have greater uncertainty and conflict surrounding these products.

Finally, in addition to the clusters that positively tracked between infographic differences in risk perception, we also observed a small cluster that was negatively correlated with mean risk

differences in the lingual gyrus (P = .030). The lingual gyrus is associated with vision and visual memory (Macaluso et al., 2002).

Activation related to attitude processing. Six clusters of activation were positively associated with positive attitude differences (higher activation for more positive attitudes; Figure 4; Table 2) between the infographics, and nine clusters were negatively associated with positive attitude differences between the infographics (higher activation for more negative attitudes; Figure 4; Table 2). The positively associated regions included the a priori region of interest ventromedial prefrontal cortex (P = .049), along with dorsal anterior cingulate cortex (ACC; P < .001), two clusters in the precuneous (cluster 1: P < .001; cluster 2: P = .026), the supramarginal gyrus (P = .007), and the lingual gyrus (P = .030).

The ventromedial PFC was predicted to correlate with positive attitudes given this region tends to track subjective value (Levy and Glimcher, 2012; Bartra et al., 2013) as well as positive affect more generally (Roy et al., 2012). The ventromedial PFC activation is depicted, along with the whole brain activation, in Figure 4. As the bar graph illustrates, this region again primarily distinguished between the low attitude (higher perceived risk; antibiotics and hormones) technologies and the higher attitude technologies. Note that the overall direction of activation is deflected negative in medial PFC, which simply reflects its lower activation relative to the baseline fixation periods. This negative deflection is typical in cognitive tasks as this brain region is part of the “default mode network,” a network of regions that tend to be more active during rest than during cognitive tasks and tend to be associated with more inwardly focused attention and self-referential processing (Raichle, 2015).

The dorsal ACC was not predicted to track positive attitudes *a priori*, but is involved with general cognitive conflict resolution (Weissman et al., 2004). The fact that these conflict-related areas were positively correlated with attitudes suggests, perhaps, that some conflict or conflict resolution was involved in processing the infographics associated with more positive attitudes. However, it is not possible to fully infer this from the brain region activation alone (Poldrack, 2006), and thus the specific role these conflict-related areas may be playing is an important question for future research.

In addition to the prefrontal regions, we again observed a cluster in the lingual gyrus that tracked positive attitudes, as we did for the risk processing analysis. We also observed two clusters in the precuneus that tracked positive attitudes, another brain region that is involved in the default mode network and associated with episodic memory and self-reflection (Cavanna and Trimble, 2006). Finally, we observed a cluster in the supramarginal gyrus that tracked positive attitudes, a region of the parietal cortex associated primarily with reading and language function (Price, 1998), but also linked with measures of moral reasoning in decision making (Reniers et al., 2012) and automatic influences of brand information in consumer choice (Deppe et al., 2005).

Clusters that were negatively associated with between-infographic differences in positive attitudes were bilateral (both sides of the brain) lateral PFC regions (both $P < .001$), the left of which overlaps with the cluster revealed for the risk perception analysis, as well as superior parietal regions that overlapped with the risk results (both $P < .001$). These results suggest that some of the same regions involved with processing risk are associated with processing more general attitudinal information, which is expected, as perceived risk and more general attitudes toward food technologies are often intertwined (Eiser et al., 2002). However, given the attitude

infographic processing sections were separate from the risk processing sections, these results serve as an important internal replication of the risk results on separate data. Thus, the lateral PFC and parietal results are particularly robust in the sense that they hold in both risk and attitude processing. In addition to the clusters that overlapped with the risk processing clusters, we observed clusters that were negatively associated with attitudes in several visual regions including bilateral inferior temporal gyrus (both $P < .001$), a region involved in basic visual object categorization, and the occipital pole ($P = .006$), a region involved in very basic visual processing. Finally, we also observed activation in the cerebellum that was negatively associated with attitudes ($P < .001$), which is most commonly associated with motor learning, but may also play some roles in attentional processing (Gottwald et al., 2003).

Individual Differences in Attitude Change

In addition to examining overall risk and attitudes associated with the infographics, we wanted to examine whether any brain regions were predictive of an individual's change in attitudes or risk perception toward the food technologies. To this end, we standardized participants pre- and post-infographic attitudes and risk scores using the means and standard deviations of the normative online sample, as per the behavioral results. We then used the difference between the standardized pre- and post-infographic measures as measures of how much an individual changed their attitudes and perceptions of risk after seeing the infographics. These measures of attitude and risk perception change were entered into third-level whole-brain GLM analysis to test which brain regions were significantly associated with individual differences in risk and attitude change.

Two of these analyses showed significant results: change in risk perception for the hormone infographic and change in attitudes for the GMOs infographic. For the hormone

infographic (Figure 5A, 5C; Table 2), we found four clusters that were significantly associated with change in risk perception: bilateral lateral PFC (Left: P = .01; Right: P = .006), superior frontal gyrus (P = .01), and frontal pole (P = .006). Specifically, these regions were positively associated with change in risk perception, which indicates that these regions were associated with either resisting change in risk (since most participants decreased) or increasing perceptions of risk. These results help to interpret the within-subject lateral PFC effects, where the lateral PFC was associated with higher risk and lower attitudes across the infographics. Specifically, they suggest that the lateral PFC may be inhibiting attitude change for hormones, as opposed to encouraging attitude change. However, these results seem to be specific for hormones as they did not appear for any of the other risk change measures. Reasons for why this result may be specific to hormones are discussed below.

In addition to the hormone results, we found three significant clusters that were positively associated with attitude change for GMOs (higher activation for more positive attitude change): in the supramarginal gyrus (P < .001), the thalamus (P = .01), and left cerebral white matter (P = .02; Figure 5B & 5C; Table 2). The supramarginal gyrus overlaps with positive attitude results in the between-infographic analysis and may indicate either language-related processing or perhaps decisional factors, as discussed above in the attitudes section. The thalamus and white matter are not easily related to any single cognitive function and may simply indicate some sort of global cognitive or affective engagement.

DISCUSSION

Food technologies play an important role in food quality, sustainability, and global food security, yet technological innovation is often met with resistance from consumers. The present study used neuroimaging to reveal how the brain processes information related to food

technology topics and how these neurobiological processes vary with perceived riskiness and attitudes associated with the technologies. Participants viewed infographics about six different food technology topics including antibiotics, hormones, GMOs, vaccines, sustainability, and animal welfare. We found that activation in lateral PFC tracked between-infographic differences in risk perception and attitudes and was most activated for the higher perceived risk / low attitude topics antibiotics and hormones. Contrastingly, ventromedial PFC activation tracked positive attitudes and was most activated for the higher perceived attitude topics (GMOs, vaccines, sustainability, and animal welfare). In addition to our primary, between-infographic results, we found individual differences in risk perception change for hormones was negatively correlated with lateral PFC activation, suggesting that, for this topic, higher lateral PFC activation was associated with resistance to attitude change. Finally, part of the supramarginal gyrus was positively correlated with individual differences in attitude change for GMOs.

The fMRI results present a critical step forward in understanding consumer attitudes and risk perceptions surrounding food technology. Because education and accurate dissemination of information are critical tools for reducing consumer resistance to technological development, it is important to understand how processing such information is related to differences in attitudes and risk perception. Functional neuroimaging provides a promising window into consumer information processing as it has the potential to show—above and beyond self-report surveys—which information is being processed overall more positively, by examining how activation in regions associated with positive subjective value, such as the ventromedial PFC, track attitudes and risk perception. It also has the potential to uncover which information is being processed more effortfully, which tends to activate regions associated more with uncertainty processing. Brain activation patterns can thus reveal how and whether informational campaigns are leading

to effective processing by consumers, and thus potentially index attitude and risk perception change.

Despite the success of the current study at identifying regions that track attitude and risk perception differences between food technologies, it is important to note that it remains unclear whether attitudes are affecting how the information about the technologies is being processed or are a reflection of the information the infographics contain. For example, the increased ventromedial PFC may reflect more positive attitudes toward animal welfare technologies and sustainability in general, or may reflect the fact that participants like the contents of these infographics better. Future research will need to dissociate individuals' baseline affective and cognitive information about food technology topics from the information present in the infographics and determine how these factors overlap. Nevertheless, the current results point to critical connections between infographic processing and attitudes/risk perception that are useful for understanding how consumers approach information about food technologies.

The present results complement and extend previous fMRI studies on willingness-to-pay for foods (e.g., milk, eggs) produced with food technologies. Previous studies have largely focused on the same lateral PFC regions that we identified here. The lateral PFC tends to be more active when participants are considering both price and technology in willingness-to-pay judgments and track's participants' choices to opt for more expensive organic or natural choices (Linder et al., 2010; Lusk et al., 2015). These results are related to the present finding that the lateral PFC tends to activate more for the less positive attitude, higher perceived risk technologies and may reflect the same general uncertainty-related mechanism. When people are confronted with technologies that conflict with their preferences, the lateral PFC may be engaged to help them resolve this uncertainty. Likewise, consistent with previous findings that the

ventromedial PFC tracks the outcomes of willingness-to-pay judgments (Crespi et al., 2015), we found the ventromedial PFC tracks overall positive attitudes for the technologies.

What is critical about the present results, relative to previous willingness-to-pay studies, is that such lateral PFC and medial PFC activation are connected to information processing surrounding technologies outside of choice-related contexts. This suggests that the activation found in previous willingness-to-pay studies may not reflect simple trade-offs between price and technology, but more basic pre-decisional attitudes that feed into such choice trade-offs. For example, it may be the case that lateral PFC activation during a choice to pay more for organic foods specifically reflects negative attitudes toward technologies as opposed to uncertainty about the decisions per se. Whether the PFC activation observed in previous studies reflects an attitudinal “input” into the decision process or an “outcome” of the decisional process (see e.g., Davis et al., 2009) is an important question for future research. In many cases, attitudes, risk perception and decision processes are tightly coupled, and thus the practical upshot—that people will pay to avoid technologies that generate conflict—may be the same in both scenarios.

In addition to its relation to neuroimaging research on food technologies, the present study has important relationships to neuroeconomic research more generally. The neuroeconomic literature has often focused on the topic of risk processing using the economic definition of risk as uncertainty in outcome (Schonberg et al., 2011). This contrasts with the use of the term risk in everyday language, which tends to be more related to perceived potential for negative outcomes. The risk perception measures we used in the present study are more directly connected to people’s perception of negative consequences from technologies, and thus the overlap between our results and studies of economic uncertainty is potentially enlightening. Indeed, as discussed above, the lateral PFC tends to track uncertainty in economic decision

making tasks; as a result, the present finding that it also tracks differences in risk perception between the technology infographics has the potential to unite these different areas. An important question is whether the lateral PFC tracks both economic uncertainty and risk perception separately or perhaps both follow from a more basic cognitive function, such as cognitive control processes. Given the role that uncertainty plays in risk perception more broadly (Slovic, 2016), the current results also open the possibility that the lateral PFC is specifically where uncertainty gets incorporated into people's beliefs about the potential negative outcomes associated with technologies.

In addition to its higher activation for technologies that were perceived as higher risk, our finding that lateral PFC activation was negatively correlated with individual differences in change in risk perception for hormones gives important information about the lateral PFC's potential function in the present context. The lateral PFC has been shown in previous studies to track individual differences in decision making and cognitive performance (Christopoulos et al., 2009; Schonberg et al., 2011; Worthy et al., 2016). Although the lateral PFC has been shown to track participants' willingness to pay more to avoid food technologies and is often associated with individual differences in risk aversion, other results suggest that activation in lateral PFC may not always be associated with increases in negative attitudes or perceived risk. Indeed, a recent study on willingness to pay for animal welfare technologies in egg production has shown that lateral PFC may more generally reflect updating of willingness-to-pay based on information (McFadden, et al., 2015). This could mean that lateral PFC activation is not necessarily positively or negatively related to acceptance of a technology, but may simply reflect controlled deliberation (i.e., elaboration; Petty and Cacioppo, 1986). The outcome of such controlled deliberation may be an increase or decrease in attitudes, depending on several factors such as

argument strength, personal relevance, cognitive ability, and participants' motivations for changing their attitudes (Priester et al., 2009). For example, here lateral PFC was associated with resistance to changing risk perception for hormones, but perhaps with different arguments or with participants motivated to change their risk perceptions, it may have been associated with improvements in attitudes.

The idea that lateral PFC may reflect differences in the outcomes of attitude processing between participants who processed the information centrally versus peripherally (Petty and Cacioppo, 1986) may explain why we did not see many other large individual difference effects for the other technologies. Under this explanation, an individual difference effect should only be observed in a brain region to the extent that the brain region governs a process that is differentially engaged between individuals (e.g., central vs. peripheral processing), and the differential activation of this process leads to differences in attitude ratings. In the case of the infographics that did not show an individual difference effect in the lateral PFC, it is possible that people did vary in terms of how effortfully they processed the information, but perhaps, in these cases, both central and peripheral processing had equivalent attitudinal effects. This hypothesis suggests that future work relating lateral PFC activation to attitudes and risk perception will benefit from looking at arguments that differ in terms of their effects on attitudes depending on whether people use effortful or more automatic processes. In this way, fMRI has the potential to be a useful applied technique for vetting educational and branding-related information to test whether more effortful processing of the presented information is leading to better or worse attitudes, or if it has a homogeneous effect across processing strategies. Further, on a more theoretical level, if our hypotheses about the connections between our results and theories of persuasion are borne out, fMRI could become a key tool for measuring neural latent

variables related to central and peripheral processing as well as attitude strength and value, much as it has in other areas of "model-based" fMRI (e.g., O'Doherty et al., 2007; Davis et al., 2012; Turner et al., 2017).

One limitation of the present study is that the infographics we employed contained a wide range of varied strategies to convey the safety and utility of the food technologies. Thus, it is not possible to separately conclude which aspects of the infographics may have been stronger or weaker in influencing attitudes and risk perception, or brain activation, the most. For example, the hormones infographic contains information highlighting the low tissue accumulation of hormones from hormone implants, relative to other dietary sources of estrogen, information about sustainability and environmental benefits, and the fact that the implants replace some naturally occurring hormones that are removed by food production practices. Any of these strategies could be leading to the observed attitude and risk perception results and activation for this infographic. Future studies interested specifically in isolating cognitive and neurobiological factors that lead to increases in attitudes and consumer acceptability may wish to constrain the arguments to be presented in more serial fashion to isolate their individual effects. Nevertheless, the use of real-world infographics offers a strong, ecologically valid simulation of how participants may encounter information about food technologies outside of the laboratory. The tight coupling we observed between participants' attitudes and risk perception and brain activation suggests that fMRI may be useful for screening such infographics before public information campaigns are deployed.

CONCLUSIONS

The present study examined the neurobiological processes engaged when participants viewed information related to food technologies. We found that areas of the lateral PFC tracked

heightened risk perception and lower attitudes for technologies, whereas the medial PFC tracked positive attitudes. These results give a unique window into the minds of consumers, as they illustrate how differences in attitudes and risk between food technologies affect basic information processing in the brain. Connections between the basic attitudinal-risk processing and individual differences in activation suggest that functional neuroimaging may be a useful tool for assessing how people process informational materials about the benefits of food technologies, which may lead to more effective strategies for combatting resistance to such technologies. Indeed, to promote increasing advances in food quality, sustainability, and security, technological innovation will continue to be critical, and consumer acceptance of such innovation will continue to play a large role in determining whether it succeeds.

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Figure Captions

Figure 1. An example of the infographics presentation phase for the fMRI task. One cycle of the task would give participants a cue for what to consider in the following infographic (risks, attitudes, benefits). Then they completed 6 survey questions before the next cycle began. The +'s indicate random fixation that was interspersed to allow the fMRI signal to be separated between different task components.

Figure 2. Mean post-infographics behavioral ratings for risk (A) and attitudes/benefits (B). The ratings were obtained during the scanning blocks after the infographic presentations. The error bars indicate +/- 1 standard error of the mean.

Figure 3. (A) Brain regions positively correlated with between infographic differences in risk during the risk processing blocks (red; greater activation = higher risk) and brain regions negatively correlated with between infographic differences in risk during the risk processing blocks (blue; greater activation = lower risk). (B) A bar graph depicting the pattern of activation within the observed lateral PFC cluster. The red bars indicate activation in this region during the risk processing blocks (when participants were asked to process the infographics with respect to risk). The yellow bars indicate activation during the independent attitudes processing blocks (when participants were asked to process attitudes or benefits).

Figure 4. (A) Brain regions positively correlated with between infographic differences in attitudes during the attitude rating blocks (red; greater activation = higher attitudes) and brain regions negatively correlated with between infographic differences in attitudes during the

attitude rating blocks (blue; greater activation = lower attitudes). **(B, C)** A bar graph depicting the pattern of activation within the observed medial **(B)** and lateral **(C)** PFC clusters. The red bars indicate activation in this region during the risk processing blocks (when participants were asked to process the infographics with respect to risk). The yellow bars indicate activation during the independent attitudes processing blocks (when participants were asked to process attitudes or benefits).

Figure 5. (A) Results from the whole brain analysis identifying areas that are positively correlated with change in risk perception for hormones. (B) Scatterplot illustrating association between the right lateral PFC and change in risk perception for hormones. (C) Results from whole brain analysis identifying areas that are positively associated with change in attitudes for GMOs. (D) Scatterplot illustrating association between right supramarginal gyrus and change in attitudes for GMOs. Note that the scatterplots in these figures are primarily suitable for evaluating the relationship (e.g., the direction of association, linearity assumption) depicted in the brain maps and do not constitute independent statistical tests (Friston, 2012).

Tables

Table 1

Demographics

N	53
Age	18-43 *M* = 23.1, *SD* = 5.6
Sex	Male = 22 (41.5%) Female = 31 (58.5%) Other = 0 (0%) Prefer not to say = 0 (0%)
Ethnicity	Asian-American = 1 (1.9%) Black or African American = 9 (17.0%) Hispanic = 14 (26.4%) Native American = 0 (0%) Native Hawaiian = 0 (0%) White or European = 26 (49.1%) Other = 3 (5.7%) Prefer not to say = 0 (0%)
First language	English = 47 (88.7%) Arabic = 2 (3.8%) Portuguese = 1 (1.9%) Spanish = 4 (7.5%)
Highest Level of Education	Middle or junior high school = 0 (0%) Some high school = 4 (7.5%) Some college = 31 (58.5%) College degree = 6 (11.3%) Some post-graduate work = 2 (3.8%) Post-graduate degree = 10
Household income	< 10k = 12 (22.6%) 10k-19.9k = 8 (15.1%) 20k-29.9k = 5 (9.4%) 30k-39.9k = 2 (3.8%) 40k-49.9k = 1 (1.9%) 50k-59.9k = 4 (7.5%) 60k-69.9k = 3 (5.7%) 70k-79.9k = 2 (3.8%) 80k-89.9k = 9 (17.0%) 90k-99.9k = 10 (18.9%) 100k-149.9k = 5 (9.4%) >150k = 3 (5.7%)
Political Orientation	Very liberal = 5 (9.4%) Somewhat liberal = 20 (37.7%)

	Neither liberal nor conservative = 15 (28.3%) Somewhat conservative = 10 (18.9%) Very conservative = 3 (5.7%)
Buys organic	Only buy organic = 0 (0.0%) Buy organic when alternative exists = 5 (9.4%) Frequently buy for select produce = 20 (37.7%) Only when convenient or affordable = 3 (5.7%) Rarely buy = 8 (15.1%) Don’t pay attention to organic = 2 (3.8%) Don’t buy organic = 15 (28.3%)
Eats meat	Yes = 51 (96.2%) No = 2 (3.8%)
Dietary philosophy	Vegan = 1 (1.9%) Vegetarian = 2 (3.8%) Pescatarian = 1 (1.9%) Paleo = 3 (5.7%) Carnivore = 3 (5.7%) Omnivore = 9 (17.0%) Low Calorie = 6 (11.3%) Low Sodium = 4 (7.5%) I just eat what I like = 45 (84.9%) Other = 5 (9.4%)

Table 2

fMRI Results

Contrast	Region	Cluster size (*k*)	Cluster *p*-value	Peak MNI coordinate <x,y,z>	Peak Z
Mean risk correlation > 0 (positively correlated with perceived risk)					
	Lateral prefrontal cortex (dorsolateral and inferior frontal gyrus)	1496	<.001	<-48,28,2>	5.20
	Superior and middle temporal gyrus / temporo-parietal junction	458	<.001	<-54,-36,0>	4.82
	Left lateral occipital cortex/ superior parietal lobule	318	.002	<-28, -60, 42>	4.24
	Right lateral occipital cortex/ superior parietal lobule	170	.040	<38, -58, 44>	4.03
Mean risk correlation < 0 (negatively correlated with perceived risk)					
	Lingual gyrus	175	.030	<10, -60, 4>	4.36
Mean attitudes correlation > 0 (positively correlated with attitudes					
	Dorsal anterior cingulate cortex	585	<.001	<-4,24, 20>	4.54
	Precuneous / posterior cingulate cortex	512	<.001	<0,-40,46>	4.44
	Supramarginal gyrus	229	.007	<62,-36,36>	3.88
	Lingual gyrus	188	.03	<-30,-44,-6>	4.52
	Precuneous	173	.026	<-14,-64,22>	3.96
	Ventromedial prefrontal cortex / ventral anterior cingulate cortex	147	.049	<-12,46,-2>	4.24
Mean attitudes correlation < 0 (negatively correlated with attitudes)					
	Left middle frontal gyrus (dorsolateral PFC) and inferior frontal gyrus	1765	<.001	<-48,12,36>	5.38
	Left lateral occipital	999	<.001	<-26,-58,42>	5.11

cortex/superior parietal lobule				
Left inferior temporal gyrus	968	<.001	<-46,-56,-12>	5.73
Right occipital pole	745	<.001	<36,-92,2>	4.83
Cerebellum	670	<.001	<-6,-80,-32>	4.57
Right middle frontal gyrus (dorsolateral PFC)	648	<.001	<50,24,28>	4.63
Right lateral occipital cortex / superior parietal lobule	393	<.001	<34,-56,52>	4.54
Right inferior temporal gyrus	379	<.001	<54,-50,-12>	4.97
Left occipital pole	239	.006	<-28,-94,-8>	4.47
Hormone Risk Change (positively correlated with change in risk)				
Right frontal pole	230	.006	<28,52,20>	4.28
Right middle frontal gyrus (dorsolateral PFC)	229	.006	<40,2,56>	4.02
Left middle frontal gyrus (dorsolateral PFC)	194	.01	<-30,0,58>	3.98
Superior frontal gyrus	194	.01	<2,48,38>	3.36
GMO Attitude Change (positive correlated with change in attitude)				
Supramarginal gyrus	708	< .001	<56,-38,26>	5.53
Thalamus	214	.01	<-22,-20,12>	5.14
White matter	198	.02	<-30,-30,30>	4.19

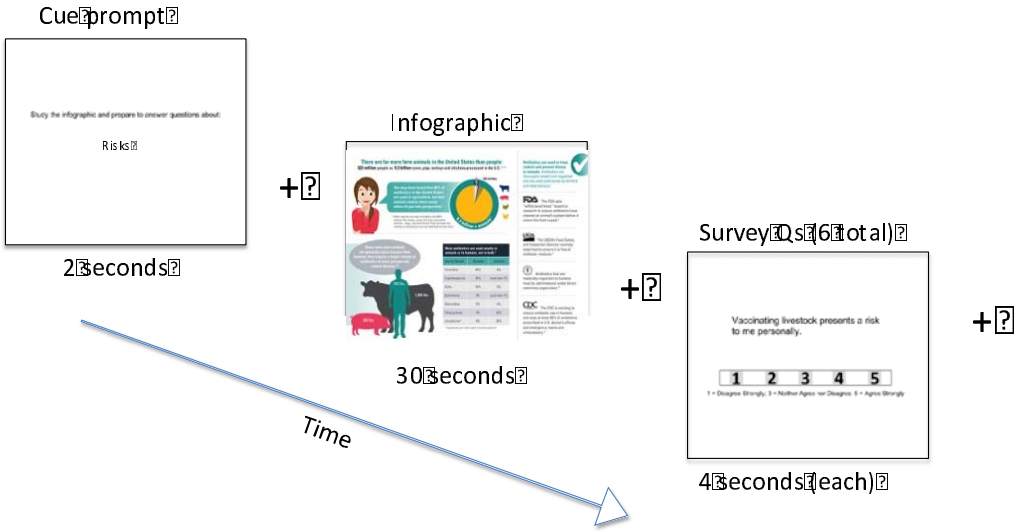


Figure 1. An example of the infographics presentation phase for the fMRI task. One cycle of the task would give participants a cue for what to consider in the following infographic (risks, attitudes, benefits). Then they completed 6 survey questions before the next cycle began. The +'s indicate random fixation that was interspersed to allow the fMRI signal to be separated between different task components.

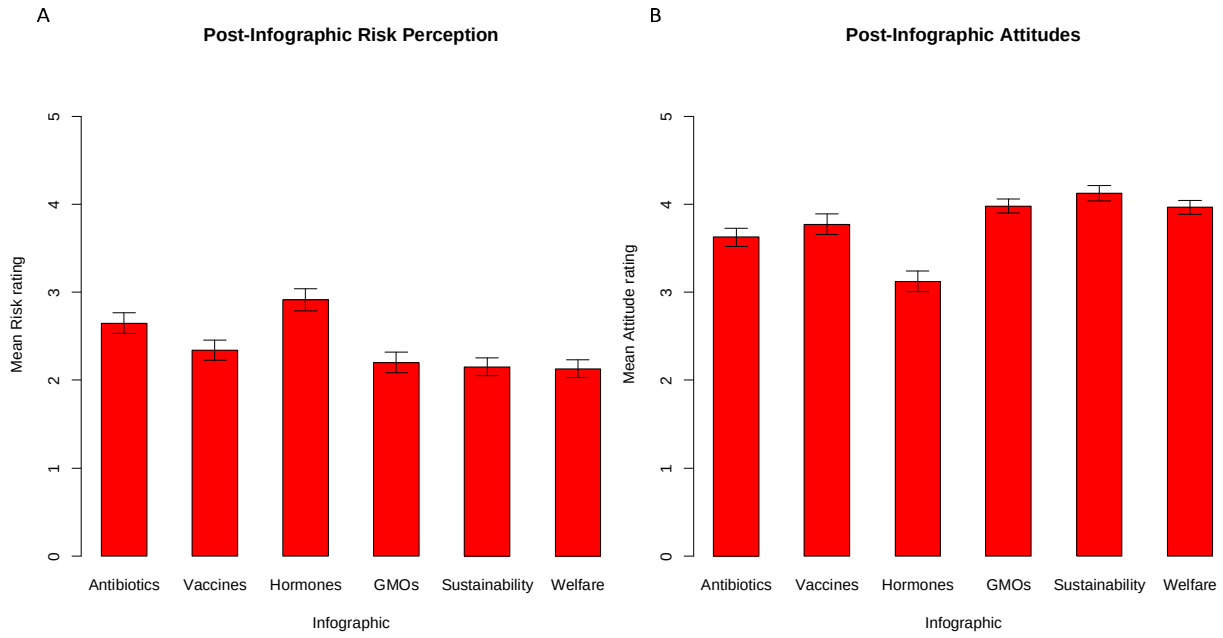


Figure 2. Mean post-infographics behavioral ratings for risk (A) and attitudes/benefits (B). The ratings were obtained during the scanning blocks after the infographic presentations. The error bars indicate +/- 1 standard error of the mean.

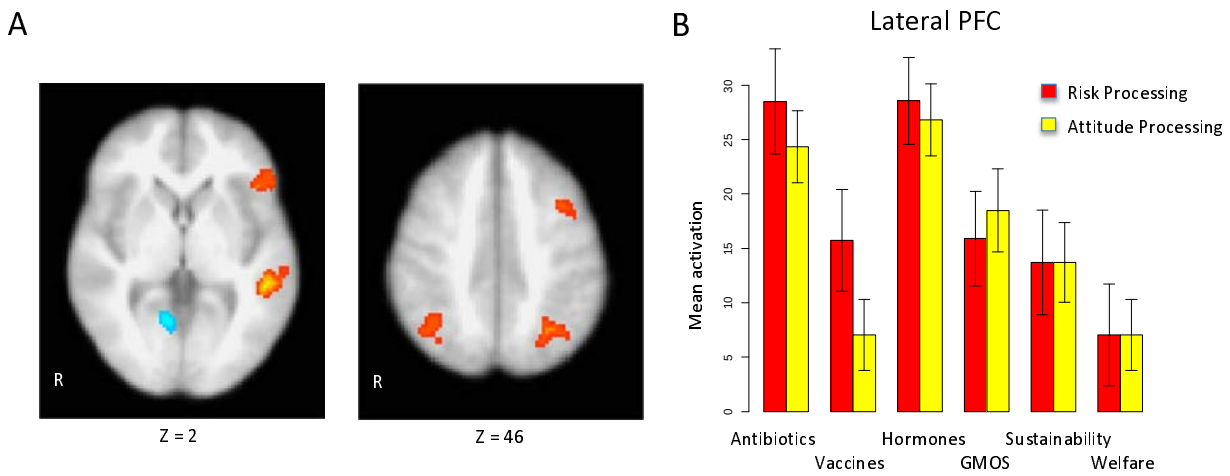


Figure 3. (A) Brain regions positively correlated with between infographic differences in risk during the risk processing blocks (red; greater activation = higher risk) and brain regions negatively correlated with between infographic differences in risk during the risk processing blocks (blue; greater activation = lower risk). (B) A bar graph depicting the pattern of activation within the observed lateral PFC cluster. The red bars indicate activation in this region during the risk processing blocks (when participants were asked to process the infographics with respect to risk). The yellow bars indicate activation during the independent attitudes processing blocks (when participants were asked to process attitudes or benefits).

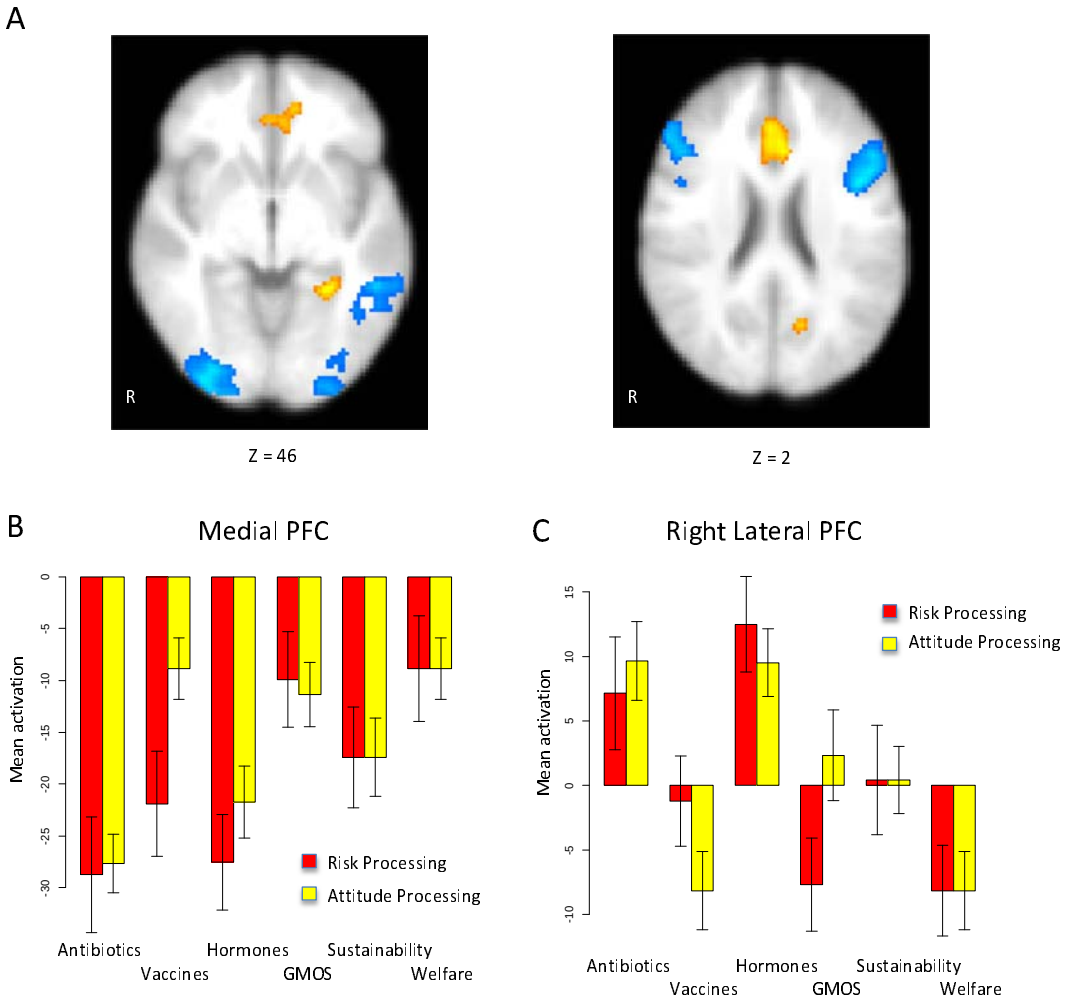


Figure 4. (A) Brain regions positively correlated with between infographic differences in attitudes during the attitude rating blocks (red; greater activation = higher attitudes) and brain regions negatively correlated with between infographic differences in attitudes during the attitude rating blocks (blue; greater activation = lower attitudes). **(B, C)** A bar graph depicting the pattern of activation within the observed medial **(B)** and lateral **(C)** PFC clusters. The red bars indicate activation in this region during the risk processing blocks (when participants were asked to process the infographics with respect to risk). The yellow bars indicate activation during the independent attitudes processing blocks (when participants were asked to process attitudes or benefits).

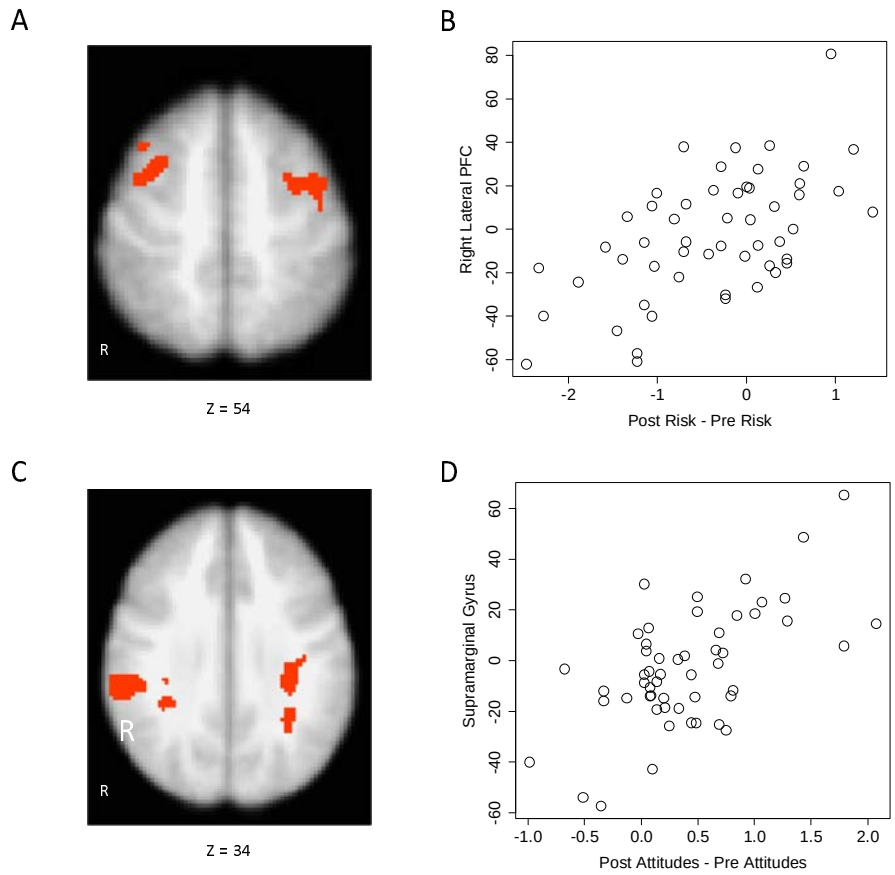


Figure 5. (A) Results from the whole brain analysis identifying areas that are positively correlated with change in risk perception for hormones. (B) Scatterplot illustrating association between the right lateral PFC and change in risk perception for hormones. (C) Results from whole brain analysis identifying areas that are positively associated with change in attitudes for GMOs. (D) Scatterplot illustrating association between right supramarginal gyrus and change in attitudes for GMOs. Note that the scatterplots in these figures are primarily suitable for evaluating the relationship (e.g., the direction of association, linearity assumption) depicted in the brain maps and do not constitute independent statistical tests (Friston, 2012).

Supplemental Materials

Supplemental Table 1

Technology-Specific Survey Questions

Asked for each technology

5-point scale: *strongly disagree, somewhat disagree, neither agree nor disagree, somewhat agree, strongly agree*

Technologies / phrasing:

vaccinating livestock/ vaccinated livestock.

sustainable food technology (/ies)

using hormones on livestock/hormone treated livestock

genetically modified (GM)

using antibiotics on livestock/ antibiotic treated livestock

animal welfare technology

Familiarity (pre only)

1. I am familiar with the practice of t.

2. I am knowledgable about the practice of t.

Perceived Norms (pre only)

1. Most people who are important to me approve of t.

2. Most people who are like me support t.

Trust in Science (pre only)

1. Scientists understand the risks posed by t.

2. I trust scientists to explain the risks posed by t.

Past Behavior (pre only)

1. In the past three months, I have consumed food produced from t.

2. In the past three months, I have avoided food produced from t.

Perceived Control (pre only)

1. I am able to control how much I am exposed to food produced from t.

2. I am able to avoid purchasing food produced from t.

Risks

Pre:

1. The risks posed by t are acceptable.

2. t presents a risk to the global food supply.

Post:

1. t presents a risk to the environment.

2. t presents a risk to me personally.

3. t presents a risk to future generations.

4. People are likely to suffer negative health consequences from t for food production.

5. There is no safe level of exposure to food (dairy, eggs, meat) from t.

6. Even a small amount t affects the safety of food.

Attitudes (personal)

Pre:

1. I intend to support the use of t for food production.

2. It is good to buy food produced from t.

Post:

1. Consuming food produced from t is healthy.

2. I approve of t.

3. Food produced from t should be available for everyone.

4. t for food production is smart.

5. Overall, t is a good application of technology.

6. I would rather purchase food produced from t.

Attitudes (benefits)

Pre:
1. t benefits society.

2. t the environment.

Post:
1. t benefits me personally.

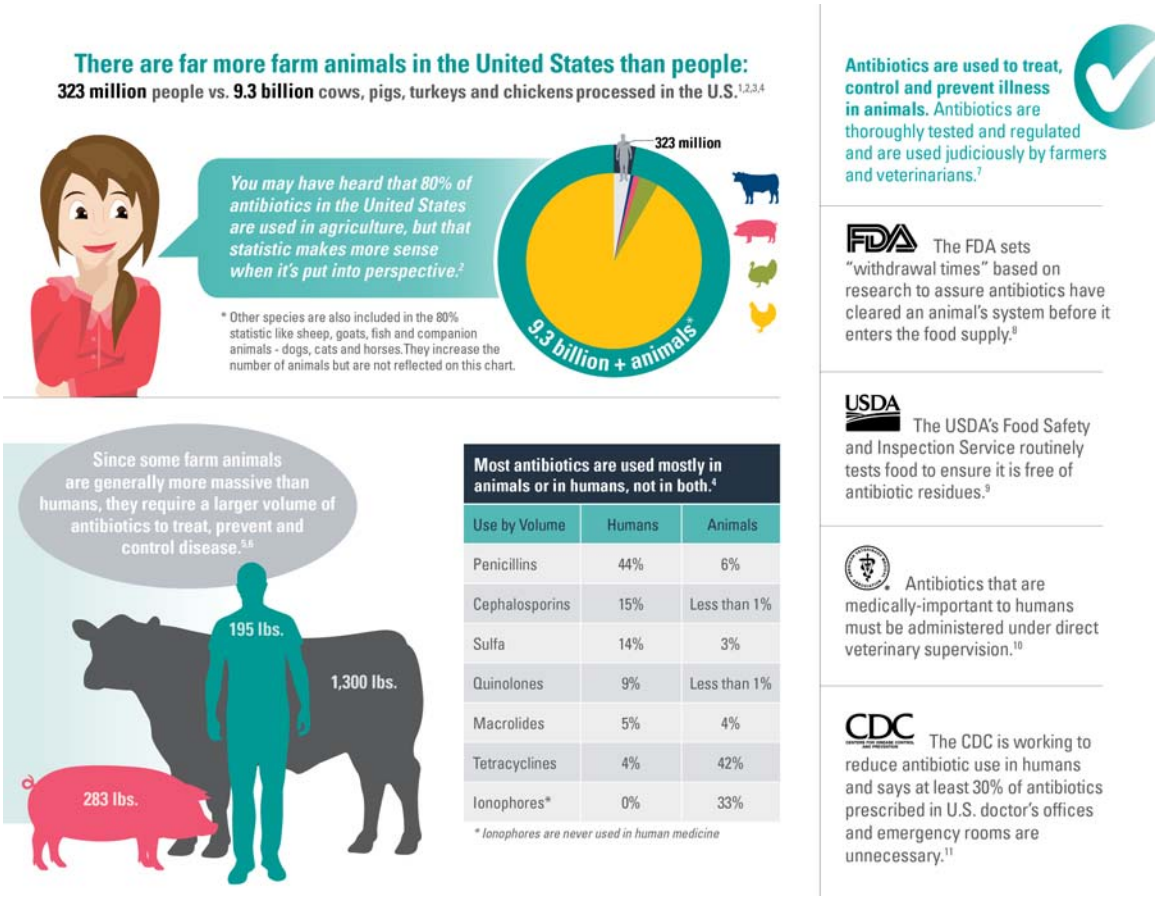
2. t benefits the livestock.

3. t promotes animal welfare.

4. t helps make food available for everyone.

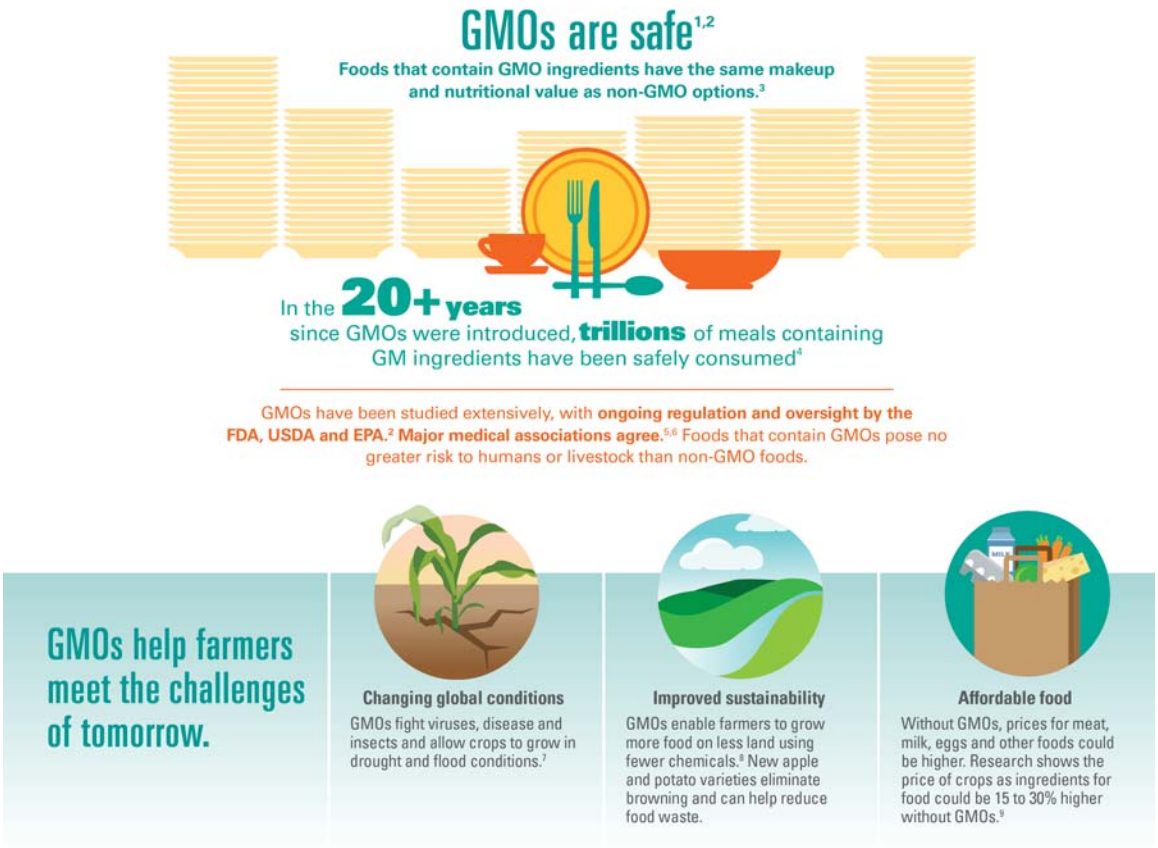
5. t helps make food affordable for everyone.

6. Overall, t is ethically sound.

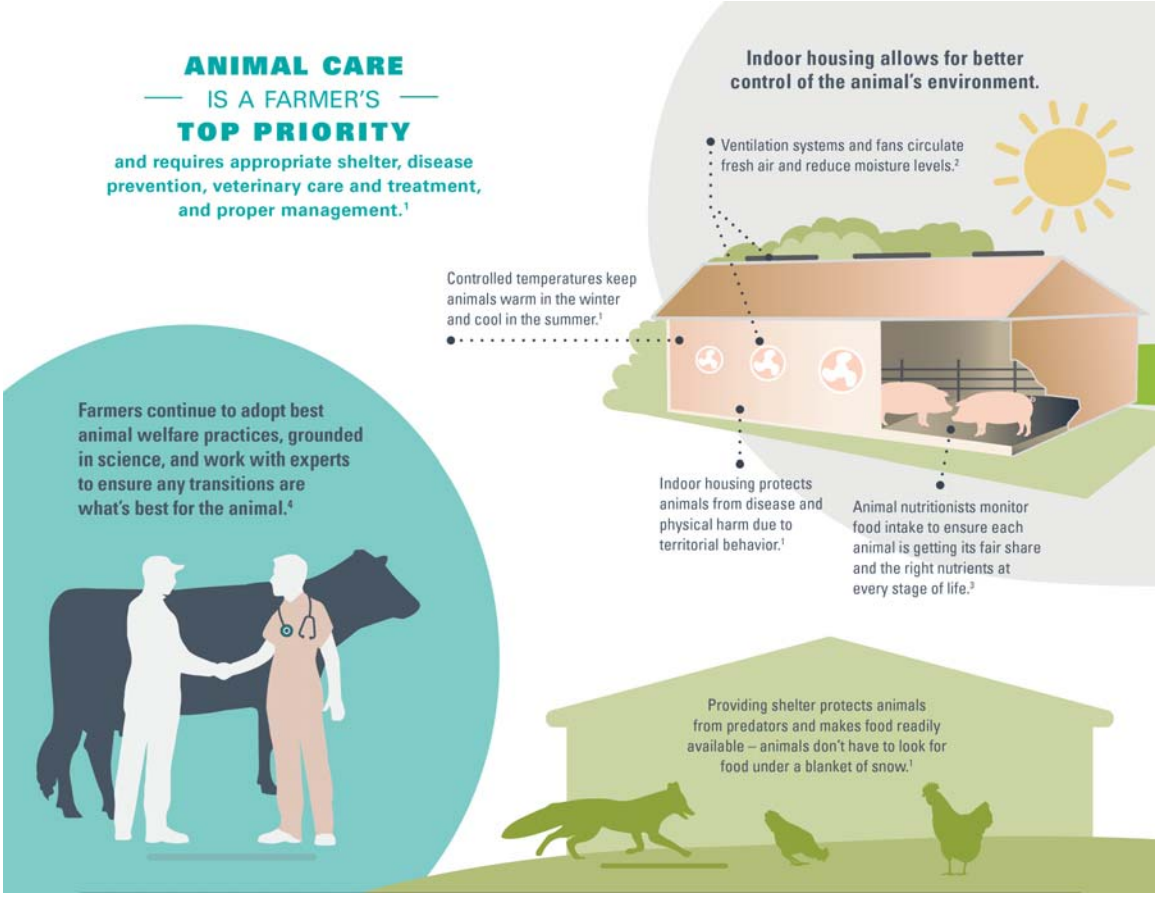


Supplemental Figure 1. Antibiotics infographic used in the study.

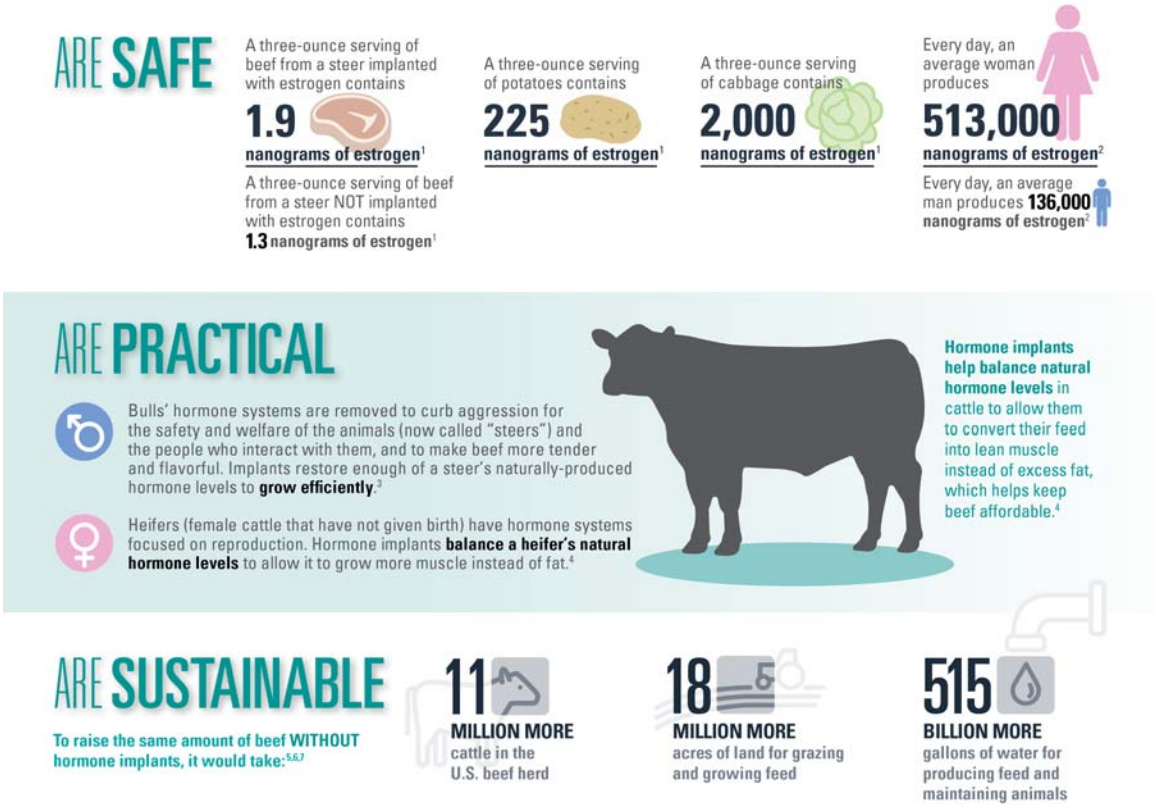
Supplemental Figure 2. Sustainability infographic used in the study.



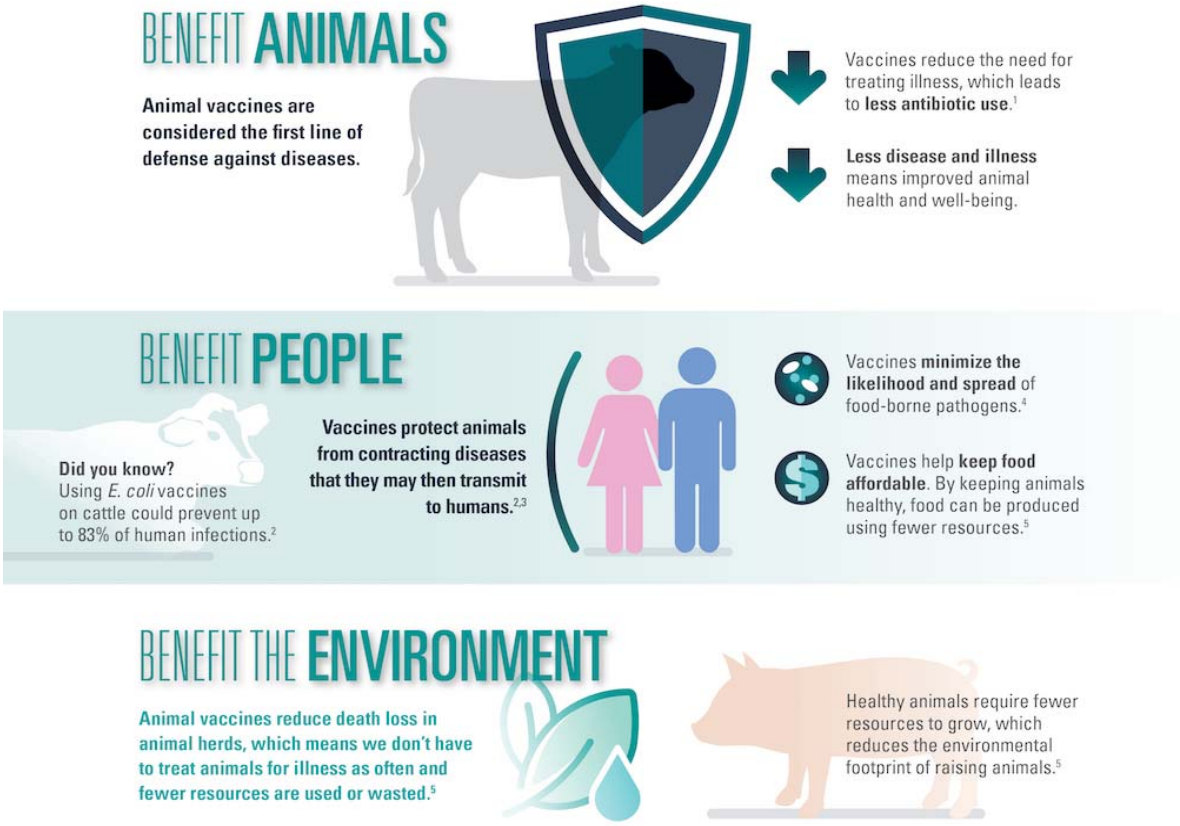
Supplemental Figure 3. GMO infographic used in the study.



Supplemental Figure 4. Animal welfare infographic used in the study.



Supplemental Figure 5. Hormone infographic used in the study.



Supplemental Figure 6. Vaccine infographic used in the study.