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How people think about the chemicals in cigarette smoke: a systematic review

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Abstract Laws and treaties compel countries to inform the public about harmful chemicals (constituents) in cigarette smoke. To encourage relevant research by behavioral scientists, we provide a primer on cigarette smoke toxicology and summarize research on how the public thinks about cigarette smoke chemicals. We systematically searched PubMed in July 2016 and reviewed citations from included articles. Four central findings emerged across 46 articles that met inclusion criteria. First, people were familiar with very few chemicals in cigarette smoke. Second, people knew little about cigarette additives, assumed harmful chemicals are added during manufacturing, and perceived cigarettes without additives to be less harmful. Third, people wanted more information about constituents. Finally, well-presented chemical information increased knowledge and awareness and may change behavior. This research area is in urgent need of behavioral science. Future research should investigate whether educating the public about these chemicals increases risk perceptions and quitting.

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Introduction

Background

Smoking is the leading preventable cause of death in the US and globally. Harms from smoking include cancer, heart disease, stroke, and respiratory disease (U.S. Department of Health and Human Services, 2014). These harms are due to constituents (chemical compounds) in tobacco and cigarette smoke (Rodgman & Perfetti, 2013), at least 72 of which are toxic to humans (Hecht, 2012). One hundred eighty countries are parties to the WHO Framework Convention on Tobacco Control (2003), a treaty that includes a requirement for countries to "adopt and implement effective measures for public disclosure of information about the toxic constituents of the tobacco products and the emissions that they may produce." In the US, the Family Smoking Prevention and Tobacco Control Act (2009) tasked the Food and Drug Administration (FDA) with collecting information from tobacco companies about the quantities of harmful and potentially harmful constituents in each brand and subbrand of regulated tobacco products and their smoke (Table 1). Some of these constituents are commonly known, such as nicotine and carbon monoxide, while many are less well known, such as acrolein and tobacco-specific nitrosamines (Hall et al., 2014).

A challenge will be to disclose constituent information in ways that are accessible to the public. The Tobacco Control Act (2009) requires the FDA to publish constituent information in a format "that is understandable and not misleading to a lay person." Additionally, the act

Table 1 FDA's abbreviated list of harmful and potentially harmful constituents

In cigarette smoke	In smokeless tobacco	In roll-your-own tobacco and cigarette filler
Acetaldehyde	Acetaldehyde	Ammonia
Acrolein	Arsenic	Arsenic
Acrylonitrile	Benzo[*a*]pyrene	Cadmium
4-Aminobiphenyl	Cadmium	Nicotine (total)
1-Aminonaphthalene	Crotonaldehyde	NNK
2-Aminonaphthalene	Formaldehyde	NNN
Ammonia	Nicotine (total and free)	
Benzene	NNK	
Benzo[*a*]pyrene	NNN	
Carbon monoxide		
Crotonaldehyde		
Formaldehyde		
Isoprene		
Nicotine (total)		
NNK		
NNN		
Toluene		

The US Food and Drug Administration (FDA) requires manufacturers to report amounts of these constituents for brands and subbrands to the agency. NNK = 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone. NNN = *N*′-nitrosonornicotine. From http://www.fda.gov/downloads/TobaccoProducts/Labeling/RulesRegulationsGuidance/UCM297828.pdf

empowers the FDA to require tobacco manufacturers to make disclosures on cigarette packs or advertisements if doing so will benefit the public health "or otherwise increase consumer awareness of the health consequences of the use of tobacco products" as long as the disclosure is not on the face of the pack or advertisement (Family Smoking Prevention and Tobacco Control Act, 2009). As the FDA decides how to share information on constituents, it is critical that the disclosures not repeat practices now known to be harmful. In the past, allowing cigarettes to be described as "low tar" or "light" may have led smokers to see them as less harmful and switch to these products rather than quitting (Gilpin et al., 2002). Optimizing constituent disclosures is a challenge that behavioral science is uniquely suited to address.

The barriers to conducting behavioral research related to tobacco constituents can be quite large given the technical and fast-changing nature of the relevant toxicology. Most behavioral scientists are unfamiliar with the toxicology literature; the relevant studies are often so biological in nature that they do not make clear to behavioral scientists what the next step is in translation. Furthermore, research on the public's awareness, knowledge, attitudes, beliefs, and behaviors regarding cigarette smoke constituents is scattered across several disconnected literatures not routinely accessed by behavioral scientists. However, with a $600 million annual budget for tobacco products, the FDA is now a major funder of behavioral science including behavioral medicine, psychology, and communication studies (U.S. Food and Drug Administration, 2016a). One of the FDA's top 10 priorities is communication about harmful chemicals in cigarette smoke constituents, one of only three key priority areas clearly in the domain of behavioral scientists (U.S. Food and Drug Administration, 2016b).

Our paper's purpose is to build behavioral scientists' capacity to contribute to this important field of research by conducting new studies and competing for available funding. To that end, we briefly review the basic science of constituents and how they harm health as a primer for behavioral scientists to understand the toxicology of constituents. We then systematically review in depth what is known about the public's awareness, knowledge, attitudes, beliefs, and behaviors with regards to cigarette smoke constituents. We also review the public's understanding of the related topics of cigarette additives and "additive-free," "natural," and "organic" cigarettes because these terms may mislead people about the presence or extent of harmful constituents. Based on the systematic review, we conclude with research opportunities for behavioral scientists that can guide regulatory actions and communication campaigns.

The science of constituents

Behavioral scientists seeking to contribute to this field may find that one of the barriers is understanding the technical and evolving knowledge about tobacco smoke toxicology.

This section provides a high-level overview of the relevant toxicology to support behavioral scientists in identifying ways to make constituent information understandable the public.

Inhaling cigarette smoke exposes people to toxic constituents, and this is the main way that cigarette use causes health harms. Cigarette smoke constituents come from a variety of sources. Some constituents originate in tobacco itself. Manufacturing can introduce additional constituents that are mixed with the tobacco, although additives are not a central source of harm (Hecht, 2012). When cigarettes burn, some constituents that were originally present in tobacco and paper become part of the smoke. Of special importance, many new constituents also form as the cigarette tobacco and paper burn. Inhaling smoke from the burning cigarette also exposes smokers to additional chemicals that may be present in the air and the cigarette filter (Hoffmann et al., 2001; International Agency for Research on Cancer, 2004; U.S. Department of Health and Human Services, 2014). Thus, constituents may come from various sources and different steps in the pathway from green tobacco leaf to cigarette smoke to the lung ("leaf-to-lung"). The quantities of each constituent can vary significantly across cigarette brands (Counts et al., 2004; International Agency for Research on Cancer, 2004; U.S. Department of Health and Human Services, 2014). Furthermore, smokers differ in their exposure due to variation in individual smoking topography, which can change how constituents pass from tobacco to smoke and through the cigarette filter (Djordjevic et al., 2000).

The multitude of constituents in cigarette smoke makes it difficult to distinguish the contribution of individual constituents to specific health outcomes, but a substantial body of evidence supports the critical role of constituents in the toxicity and carcinogenicity of cigarette smoke. Below we summarize where some key constituents become part of cigarette smoke in the "leaf-to-lung" pathway and their specific known health effects.

Respiratory toxicants

Respiratory toxicants harm the airways and lungs. Constituents that are important respiratory toxicants in cigarette smoke include acrolein, acetaldehyde, formaldehyde, and 1,3-butadiene. These toxic constituents mainly form when the cigarette burns, but some amounts form, or are introduced as contaminants, during tobacco processing and cigarette manufacturing, and later transfer to the smoke. Acrolein is one of the most powerful irritants in cigarette smoke (International Agency for Research on Cancer, 1995). It is highly irritating to the airways and eyes. It also harms the lungs' natural self-protecting ability by damaging cilia—microscopic hair-like structures on lung cells that prevent particles present in cigarette smoke and polluted air from entering the lung (International Agency for Research on Cancer, 1995). Acetaldehyde and formaldehyde also cause irritation in the airways (International Agency for Research on Cancer, 1999, 2012b). Acetaldehyde is one of the most abundant toxicants in cigarette smoke (International Agency for Research on Cancer, 2004). It causes coughing and a burning sensation in the nose, throat, and eyes (International Agency for Research on Cancer, 1999). Ammonia is another constituent that causes irritation of airways and can eventually lead to persistent coughing and other breathing problems; it forms in the smoke generated by tobacco itself and ammonia-based compounds added in the manufacturing process (Schmeltz & Hoffmann, 1977; U.S. Department of Health and Human Services, 2004; Willems et al., 2006).

Cardiovascular toxicants

Cardiovascular toxicants damage the heart and circulatory systems. Constituents that are important cardiovascular toxicants in cigarette smoke include carbon monoxide, nicotine, oxidants (such as nitrogen oxides and free radicals), hydrogen cyanide, arsenic, and acrolein (Benowitz, 2003; U.S. Department of Health and Human Services, 2010; U.S. Food Drug Administration, 2012). Both carbon monoxide and hydrogen cyanide interfere with the blood's capacity to carry oxygen (National Research Council of the National Academies, 2008; U.S. Department of Health and Human Services, 2014). Mechanisms underlying the cardiovascular toxicity of arsenic and acrolein are not well understood, but available evidence suggests that these toxicants damage arteries and interfere with the normal function of blood vessels (Perez et al., 2013; Stea et al., 2014). Nicotine and arsenic are present in tobacco itself, while other mentioned cardiovascular toxicants are mainly formed during the burning of the cigarette.

Carcinogens

Constituents that are among the most important carcinogens in tobacco products are tobacco-specific *N*-nitrosamines (TSNAs) (Hecht, 1998; International Agency for Research on Cancer, 2004, 2007). TSNAs are virtually absent in green tobacco plants, but form during tobacco leaf curing and processing from tobacco-specific alkaloids and transfer to cigarette smoke (Hecht et al., 1977; Hoffmann et al., 1976). These constituents are present only in tobacco products (Hecht, 1998; International Agency for Research on Cancer, 2007). The TSNAs NNN (*N′*-nitrosonornicotine) and NNK (4-(methylnitrosamino)-1-(3-

pyridyl)-1-butanone) cause cancers of the lung, pancreas, oral cavity, and esophagus (Hecht, 1998; International Agency for Research on Cancer, 2004, 2007).

Among other carcinogens in cigarette smoke are polycyclic aromatic hydrocarbons (PAHs) and aromatic amines that form as a cigarette burns (International Agency for Research on Cancer, 2010a, b; U.S. Department of Health and Human Services, 2001). PAHs are widely acknowledged as major contributors to lung cancer in smokers (Hecht, 1999, 2003; International Agency for Research on Cancer, 2010a; Pfeifer et al., 2002). Cigarette smoke contains many different carcinogenic PAHs, including benzo[*a*]pyrene (Ding et al., 2007; International Agency for Research on Cancer, 2010a). Additionally, aromatic amines 2-naphthylamine and 4-aminobiphenyl cause bladder cancer (International Agency for Research on Cancer, 2010a).

Metals and metalloids such as arsenic, cadmium, and lead are another group of carcinogens in cigarette smoke. These constituents are present in cigarette smoke because tobacco plants absorb them together with other elements from soil (International Agency for Research on Cancer, 2004). Arsenic and cadmium cause lung cancer and may also play a role in bladder and kidney cancers (International Agency for Research on Cancer, 2012a).

Multiple health harms

Some of the constituents discussed above pose multiple health hazards. In addition to respiratory toxicity, acetaldehyde and formaldehyde can also cause tumors in airways of laboratory animals (International Agency for Research on Cancer, 1999, 2012b), and some research suggests that acrolein is a lung carcinogen (Feng et al., 2006; International Agency for Research on Cancer, 1995). Similarly, arsenic is both a carcinogen and a cardiovascular toxicant. Of course, nicotine is not only a cardiovascular toxicant but also the main addictive agent in tobacco and cigarette smoke (Hukkanen et al., 2005). Smokers adjust the intensity and frequency of puffs during smoking to take in desired amounts of nicotine from each cigarette (Benowitz, 2001); in this way, nicotine is the major driver of exposure to all other toxicants and carcinogens present in cigarette smoke.

Methods

We systematically searched the research literature to better understand how the public may respond to information about cigarette smoke constituents. We systematically searched PubMed using these search terms in July 2016: (smok*[tiab] OR tobacco[tiab] OR cigarette*[tiab]) AND (knowledge[tiab] OR know[tiab] OR knew[tiab] OR aware*[tiab] OR attitude*[tiab] OR belief*[tiab] OR intention*[tiab] OR behavior*[tiab] OR willing*[tiab] OR susceptibility[tiab]) AND (constituent*[tiab] OR additive*[tiab] OR additive-free[tiab] OR natural[tiab] OR organic[tiab] OR emission*[tiab] OR ingredient*[tiab]). Two authors (JM and SB) independently reviewed 1713 articles' titles and abstracts. We performed a full text review of any article flagged by either reviewer. Each reviewer read half of the articles and a third reviewer (JB) independently read 20% of the articles; any discrepancies were reconciled by consensus. We then examined the 820 articles cited in the reference sections of the included articles. An evidence table summarizing these studies is available as extra supplementary material (ESM).

Results

We identified 46 relevant studies that assessed awareness, knowledge, beliefs, attitudes, or behaviors in relation to constituents in cigarettes or cigarette smoke, 31 studies from PubMed and 15 more cited in these articles (see Appendix of ESM). Thirty-eight of the articles used surveys conducted over the phone, on paper, on the internet, or in person, and seven used focus groups; other methods included document reviews and interviews. Eleven articles used experiments and fourteen used longitudinal data. Few articles used explicit theoretical or conceptual models. Unless otherwise noted, studies used convenience samples.

Constituents

Awareness and knowledge of constituents in cigarette smoke was typically low. Cross-sectional studies in the US, UK, Australia, Mexico, and Canada using convenience and probability samples have found that the public was most aware that carbon monoxide (48–86%), nicotine (64–94%), and tar (48–86%) are in cigarette smoke (Borland & Hill, 1997; Brewer et al., 2016; Cummings et al., 2004b; Environics Research Group, 1996a, b, 2003a, b; Hammond et al., 2006; Ipsos-Eureka, 2009; Moracco et al., 2016; O'connor et al., 2006; Swayampakala et al., 2015; Wiseman et al., 2016). Fewer people were aware that cyanide (13–72%) and arsenic (6–58%) are in cigarette smoke (Brewer et al., 2016; Cummings et al., 2004b; Environics Research Group, 1996b, 2003b; Hammond et al., 2006; Moracco et al., 2016; Siahpush et al., 2006; Wiseman et al., 2016), and very few people knew that other constituents such as nitrosamines (6–25%), polonium (8–24%), and mercury (11–26%) are in cigarette smoke (Boynton et al., 2016; Brewer et al., 2016; Cummings et al., 2004b; Environics Research Group, 1996b; Siahpush et al., 2006; Swayampakala et al., 2015; Wiseman et al., 2016). One study of pregnant women in Lebanon found that 70% knew cigarette smoke contained addictive substances and carcinogens (Chaaya et al., 2004). One study of a U.S. national probability sample assessed awareness of 24 cigarette smoke constituents, randomly assigning respondents to answer about a panel of four constituents (Boynton et al., 2016; Brewer et al., 2016). More than a third of participants were unaware of all of the constituents in their panel, and only 8% knew at least three of the four constituents they were asked about. Awareness of constituents was lower for participants with low educational attainment and low numeracy.

Mullins and Borland (1992) interviewed a probability sample of 305 Australian adults before a media campaign launched. They read participants a card listing the chemicals nicotine, naphthalene, methanol, lead, hydrogen cyanide, DDT, carbon monoxide, asbestos, arsenic, and ammonia. They asked participants, "To the best of your knowledge are any of those substances found in factory-made cigarettes?" Participants who answered "yes" were asked to identify the specific ones. Only 22% could correctly identify a constituent other than nicotine. Crawford et al. (2002) conducted focus groups with a diverse national population of U.S. cigarette smokers and experimenters ages 12–19 and found few could name any ingredients or chemicals that occurred naturally in tobacco. Notably, awareness of tobacco-specific nitrosamines was low, (Environics Research Group, 1996b, 2003a; Hall et al., 2014; Swayampakala et al., 2015; Wiseman et al., 2016) despite these being among the most toxic constituents.

Hall et al. (2014) surveyed an online convenience sample of U.S. adult smokers and non-smokers ($n = 300$) about 20 constituents. Most participants reported having heard of carbon monoxide (100%), nicotine (100%), ammonia (99%), formaldehyde (99%), arsenic (97%), benzene (75%), and cadmium (66%), but awareness of the remaining 13 constituents was quite low (<30%). When asked about the chemicals that are in cigarette smoke, less than 2% of participants spontaneously listed any of the 20 constituents other than nicotine (52%), ammonia (8%), arsenic (6%), and formaldehyde (3%). Only 12–30% of participants recognized any of the 20 constituents as naturally occurring in cigarette smoke, other than nicotine (76%) and carbon monoxide (73%). The researchers found that chemicals people had heard of were more likely to discourage them from wanting to smoke than unfamiliar chemicals.

Studies have also found common misperceptions relating to constituents. Across five cross-sectional studies in the US, UK, Australia, and Canada using convenience and probability samples, 30–70% of participants mistakenly believed that nicotine causes cancer (Bansal et al., 2004b; Bansal-Travers et al., 2010; Borrelli & Novak, 2007; Mooney et al., 2006; Reddy et al., 1996; Siahpush et al., 2006). One in-person survey found that, on average, 69% of respondents incorrectly believed that nicotine alone causes 14 health conditions, including strokes and respiratory conditions (Mooney et al., 2006). Among U.S. adult smokers in one cross-sectional study, about 50% of smokers believed that the reduction of nicotine makes the cigarette less dangerous and about 35% incorrectly perceived a cigarette brand low in nicotine as less addictive, (Bansal et al., 2004b; Cumming et al., 2004a). Another cross-sectional study with Swedish smokers found that 55% incorrectly believed that a relatively large part or all of the health risks in smoking came from nicotine (Wikmans & Ramstrom, 2010). A study among U.S. tobacco control professionals found that 52% did not know that tobacco-specific nitrosamines are the major carcinogens in tobacco (Biener et al., 2014).

Additives

The public knows little about additives in cigarettes. In an online study of 2,152 Belgian, French, and Swiss adults, many participants gave incorrect answers about additives (e.g., "The tobacco industry published the reasons why each additive is added to cigarettes") or said that they did not know the answer (Etter, 2007). In U.S. focus groups, most participants incorrectly believed that tobacco companies add most of the harmful chemicals to cigarettes (Moracco et al., 2016). Crawford et al. (2002) found that few participants could name any ingredients or chemicals that were added to tobacco. Hall et al. (2014) asked participants to list cigarette additives, of which the most commonly listed were nicotine (35%), formaldehyde (16%), arsenic (12%), and ammonia (12%). In a list-assisted recall task, participants most commonly categorized formaldehyde (82%), acetaldehyde (78%), and crotonaldehyde (77%) as additives, but two-thirds or more thought that almost all of the remaining 20 constituents were additives and not naturally occurring. Most importantly, participants reported higher levels of discouragement from smoking due to additives than due to naturally occurring constituents, and the vast majority of their responses about additives were incorrect.

While most participants do not know what manufacturers add to cigarettes, they appear to be more knowledgeable about why additives are added to cigarettes. Bansal-Travers and colleagues (2010) found that about two-thirds of U.S. participants correctly identified that cigarette companies use additives to make smoke easier to inhale, and most adults in a focus group study conducted by Carter and Chapman (2006) in Australia said that additives can make cigarettes more addictive and increase consumption. Etter (2007) found that 59% of Belgian, French, and Swiss adults correctly identified that additives can improve the taste of cigarettes.

"Additive-free," "organic," and "natural" cigarettes

Many Canadian high school students and U.S. adults incorrectly believed that cigarettes labeled as "additive-free," organic," or "natural" are safer than other cigarettes (Czoli & Hammond, 2014; Kelly & Manning, 2014; McDaniel & Malone, 2007). A review of tobacco industry documents found that U.S. smokers perceived "chemicals" as unhealthy and therefore a "chemical-free" cigarette was preferable (McDaniel & Malone, 2007). "Additive-free" cigarettes were perceived as less addictive, especially among U.S. adolescents (Arnett, 1999). Seventy-four percent of current adult smokers incorrectly agreed that "additive-free cigarettes have no nicotine" or responded that they did not know, and two-thirds incorrectly agreed that additive-free cigarettes contain only natural tobacco, or responded that they did not know (Cummings et al., 2004b). In a study with U.S. smokers, the average perceived safety for additive-free cigarettes ranged from 2.3 to 2.5 on a 0 to 4 scale with a higher score indicating greater belief that they were as dangerous as regular cigarettes (Bansal et al., 2004a). A national phone survey found that smokers said their interest in additive-free cigarettes would increase if they found out that cigarette smoke contains chemicals like lead and hydrogen cyanide (Brewer et al., 2016). An in-person survey found that Canadian students in grades 9–12 rated "additive-free" tobacco and "organic" tobacco as less harmful than regular cigarettes. This study found that smokers rated "additive-free" and "organic" tobacco as less harmful and more attractive than non-smokers (Czoli & Hammond, 2014). One study of a small sample of nurses found that 41% thought that cigarettes without additives are safer than regular cigarettes (Borrelli & Novak, 2007), and in another study, only 27% of current U.S. adult smokers correctly disagreed that regular cigarettes are more harmful than additive-free ones (Cummings et al., 2004b). Adolescents were twice as likely as adults to say that "no additives" meant that the cigarettes were "healthier than other cigarettes" and "less likely to harm your health" (Arnett, 1999).

Tobacco industry studies have assessed how people perceive a cigarette labelled as "natural." A 1983 tobacco industry survey of smokers found that 50% ($n = 602$) of smokers surveyed in several U.S. cities in 1983 stated that for health reasons an "all-natural" cigarette was important (McDaniel & Malone, 2007). A tobacco industry focus group study conducted in 1996 found an "all-natural" cigarette appealing because of "the absence of chemicals," which suggested a "purer smoking experience" (McDaniel & Malone, 2007). In another focus group study in 1998, one focus group of smokers rejected the idea that a cigarette could be natural at first because of its unhealthiness, but they ultimately decided that a natural menthol cigarette "would be less harmful than a regular cigarette" because cigarettes were "better without chemicals than with them" (McDaniel & Malone, 2007).

Information people want about constituents

Based on the limited literature available, the public appears interested in constituent information when it is presented in context to aid its interpretation. In Australian focus groups with adults, smokers were fascinated by the ingredients in cigarettes and their effects (Carter & Chapman, 2006). Teen smokers and experimenters in the US initially had emotional reactions to chemicals in cigarettes, but those faded as some teens concluded that the amount of chemicals is inconsequentially small or that many common items contain harmful chemicals (Crawford et al., 2002). In our own research in the US, we have found a similar fascination with constituents and desire for more information about them (Moracco et al., 2016). Participants in one study wanted the information either as a list made widely available or on cigarette packs (Crawford et al., 2002); a group of Canadian participants from a probability sample largely supported the requirement to display toxins on cigarette packs (Environics Research Group, 1996b); and another group suggested that the information be placed on the front of packs (Environics Research Group, 2003b). Australian smokers in focus groups were unaware that constituent information is provided on a government website (Carter & Chapman, 2006).

Participants had specific ideas about how to make constituent information clear and meaningful. Participants in one study wanted this information to explain the harmful effects of the constituents (Environics Research Group, 2003b). A study in France found that participants preferred descriptive information or package inserts with constituent information more than numerical information (Gallopel-Morvan et al., 2011). Another study reported that people found numerical amounts of nicotine were difficult to interpret (Etter et al., 2003). Additional studies have found that the public makes false inferences about the risks of cigarette brands based on constituent quantities provided on packs (Cohen, 1996; Gori; 1990; Hammond & White, 2012).

How well-presented constituent information affects people

Constituent information, when presented clearly, can increase awareness and knowledge of constituents, and may affect behavior. Booklets about the function of additives in cigarettes increased awareness of specific constituents (Etter, 2007). Pictorial warnings containing constituent information (e.g., a warning depicting smoke and the message, "where there's smoke there's Hydrogen Cyanide") were associated with greater awareness of and knowledge about constituents (Fathelrahman et al., 2010; Osman et al., 2013, 2016; Swayampakala et al., 2015). Similarly, providing an online sample with a poster containing constituent information increased knowledge that carcinogenic constituents contribute to disease risk and nicotine contributes to addiction (Borgida et al., 2015). Media campaigns on constituents can also increase awareness. Canada's media campaigns, combined with cigarette pack messages that include pictorial warnings and a range of constituent yields printed on the side of packs, may have been responsible for higher levels of awareness (Siahpush et al., 2006). Likewise, an Australian "What's Your Poison" campaign about constituents that showed a cigarette and listed chemicals down the side of the advertisement increased the ability to identify campaign constituents other than nicotine from 22% (pre-campaign) to 63% (post-campaign) (Mullins & Borland, 1992). Australian warnings and constituent disclosures on cigarette packs that listed amounts of tar, nicotine, and carbon monoxide and a qualitative message (e.g., "8 mg or less of nicotine– a poisonous and addictive drug") also led to increased awareness of smoke constituents (Borland & Hill, 1997). In Mexico, exposure to media campaigns that described the toxic chemicals in smoke and warnings with constituent-related messaging (e.g., "Contains thallium: Poison used in rat poison and insecticides.") produced the greatest knowledge of constituents as compared with no exposure, or exposure to either the campaign or warning by itself (Thrasher et al., 2013). Similarly, another study in Mexico found that exposure to a social media campaign increased awareness that arsenic and ammonia are in cigarette smoke (Thrasher et al., 2011).

Providing constituent information may encourage behavior change. A cross-sectional study of a probability sample of adult smokers in Australia, Canada, the UK, and the US found that participants were more likely to say they planned to quit if they were aware that carbon monoxide, cyanide, or arsenic is in cigarette smoke (Hammond et al., 2006). A study in Mexico found that exposure to pictorial warnings containing information about constituents, along with a media campaign, helped people refrain from smoking in the past month (20%) and make quit attempts since the pictorial warnings were implemented (11%) (Thrasher et al., 2013). A study of adult smokers in Scotland explored warnings written directly on individual cigarettes. The study found that warnings about decreased minutes of life or toxic constituents increased quit intentions (Hassan & Shiu, 2013). Some participants who received a booklet with information about additives said the information made them want to quit smoking (33%), although this did not affect cessation behavior (Etter, 2007). In contrast, a study in Mexico found that exposure to pictorial warnings with constituent information did not predict quit intentions, attempts, or success (Osman et al., 2013).

Discussion

Improving communication about harmful chemicals in cigarette smoke is an urgent priority internationally. Our systematic review of what people know about cigarette smoke constituents had four main findings: people know few constituents; they know little about additives and hold misperceptions about additives; they have an interest in getting more information about constituents; and providing information can increase awareness and may change behavior. Health behavior theories and related conceptualization were largely absent in this literature, leaving important gaps that behavioral scientists can contribute to closing.

Our systematic review revealed gaps in research about how people think about constituents, how to effectively communicate constituent information in a way that changes smoking behavior, and the impact of misperceptions and how to correct them. Behavioral scientists have an important opportunity to provide research that can help ensure that people correctly understand the harms posed by cigarette smoke constituents and act to reduce this risk, such as by quitting smoking. Careful research is needed to ensure we learn from and not repeat the "light" cigarettes phenomenon, in which constituent information misled smokers to believe that lower tar and nicotine quantities indicated safer cigarettes. We invite researchers from behavioral medicine, psychology, communication, health behavior, and other disciplines to help solve the problem of how to communicate with the public about constituents in a way that leads to fewer people smoking. This research may yield new insights relevant to other areas such as understanding how people think about the risks of pesticides, additives, and unhealthy ingredients when making food choices.

Research opportunity: better understanding how people think about smoke constituents

Our review found that the public has little awareness or knowledge of cigarette smoke constituents. Most Americans' exposure to constituent information has been through the U.S. Surgeon General's warning about carbon monoxide in cigarette smoke and the misleading nicotine and tar quantities published by tobacco companies in the past. Research shows that descriptive statements (rather than mere quantities) about constituents are more easily understood and associated with more accurate beliefs (Hammond & White, 2012).

One opportunity is to deepen the field's understanding of how people think about smoke constituents. Our systematic review found little use of behavioral science theories. Researchers can use these theories to better understand how the public thinks about chemicals and their risks. One approach, developed by Fischhoff and colleagues, is to build a model of how experts understand the hazard and then see how lay people's beliefs depart from the expert mental model (Bostrom et al., 1992; Fischhoff et al., 1982). For example, a parent might have a mental model that vaccination stops a disease from hurting the vaccinated child. The expert mental model however would also include that vaccines can work through herd immunity to protect unvaccinated others. By understanding gaps between lay and expert mental models, communication efforts can address these knowledge gaps and leave the lay public less vulnerable to misunderstandings. The mental models approach has been effective for a wide variety of potential hazards including nuclear power and vaccination (Downs et al., 2008; Maharik & Fischhoff, 1992). Another approach could be to better understand the simplifications that people engage in as a way to bring meaning to smoking harms. People appear to use a mental shorthand in which they equate any aspect of cigarettes with harm, for example thinking that nicotine is the main cause of the harms of smoking or that the main harms come from tobacco additives but not from burning the tobacco (Brewer et al., 2016; Moracco et al., 2016). Research on these mental shortcuts or heuristics can help the FDA and other agencies communicate about tobacco constituents in ways that match people's current mental models and address key misunderstandings.

Research opportunity: identifying key constituent communication principles

Another opportunity is to identify principles for effectively informing the public about constituents. While the Tobacco Control Act requires that constituent information be understandable and not misleading, it does not operationalize these terms. A legal review of the Act suggests that the charge can be interpreted as communicating "in a manner such that a lay person can read, comprehend, and appreciate the significance of the information" (Berman et al., in press). The Framework Convention on Tobacco Control states the task is informing the public of the "addictive nature and mortal threat posed by tobacco consumption" but this language remains to be operationalized (WHO Working Group, 2014). It is also not clear what type of understanding is most important from a public health standpoint. While studies have tried a variety of approaches for communicating information about constituents to the public, now may be the right time to more systematically determine their relative effectiveness and to identify key principles. We advocate for an approach using quick and nimble experiments, conducted in rapid succession with convenience samples, to quickly separate good from bad ideas. Noar et al. and Kelley et al. used a series of quick studies with online convenience samples to identify successful message components, which a subsequent experiment then tested in a large nationally representative sample (Kelley et al., 2016; Noar et al., 2016). Such studies allow scientists to first close in on general principles and later confirm them in costlier and more time-consuming studies with representative samples. These types of studies can test different ways of communicating information to determine what needs to be provided in order to help a lay person understand information without being misled. Study participants say that familiar cigarette smoke constituents may discourage smoking more than unfamiliar constituents. It may be that campaigns focused on increasing awareness of unfamiliar chemicals (thus making them familiar) may be effective, though this remains to be demonstrated. We do not know the boundary conditions that limit such an observation, for example whether campaigns can develop awareness of a constituent as a way to increase its ability to discourage smoking. Furthermore, campaigns that seek to correct misperceptions (e.g., that nicotine is the main source of harm in cigarette smoke) are more likely to be resisted because they require the audience to accept that a prior belief was incorrect (Lewandowsky et al., 2012).

Research opportunity: measuring behavioral outcomes

A third, and especially important, opportunity is to determine whether communications about constituents reduces smoking behavior. Informing the public and meeting legal requirements are important reasons for constituent disclosures, but a more important goal is to have fewer smokers. Studies should explore both how constituent messaging can discourage smoking initiation among youth and young adults and whether such messages can encourage and support quit attempts among current smokers. Longitudinal and intervention studies are needed to determine whether providing constituent information, either on its own or as part of other efforts, leads to lasting changes in smoking. This information on behavior change can aid the FDA and other agencies in determining the effectiveness of smoke constituent communications as a tool for tobacco control.

Research opportunity: understanding misperceptions

A final opportunity is to better understand misperceptions about cigarette descriptors, especially in the context of communication about cigarette smoke constituents. We do not yet fully understand how widespread misperceptions of descriptors such as "additive-free," "organic," and "natural" are among lay audiences. Cigarettes that use these descriptors may seem less dangerous and thus may be more enticing to people experimenting with cigarettes or smoking casually. Established smokers may also see switching to "additive-free" cigarettes as making a significant step in reducing the harms caused by constituents, thus discouraging quit attempts. Recently, some countries have begun to act on this issue. In 2014, the European Union banned any pack labeling suggesting "vitalizing, energetic, healing, rejuvenating, natural, organic properties" or making reference to the absence of additives (The European Parliment and the Council of the Eurpoean Union, 2014). In late 2015, the FDA issued warning letters to three cigarette companies that use the terms "natural" or "additive-free" in their advertising and packaging, stating that by using these terms, the products are classifiable as "modified risk tobacco products" that cannot be sold without FDA authorization (U.S. Food and Drug Administration, 2015). Regulators can better do their work when informed by research on the how the public's beliefs about these natural, additive-free, or organic products affect their behavior.

Conclusion

Studies of what people know and understand about cigarette smoke constituents have most often used quantitative approaches with multiple choice answers to assess recognition of constituents. Some have used open-ended questions and unaided recall. A few of the studies used focus groups to more richly delve into participants' ways of thinking and discussing the constituents in smoke and their relation to health harms. This multitude of approaches has worked well, providing prevalence estimates in quantitative studies, as well as the depth of meaning that qualitative inquiry develops. Most needed at this point are experiments comparing the impact of different messages and longitudinal studies to assess the impact of messages on behavior.

In sum, the public knows little about constituents but finds this information engaging and useful. Disclosure of constituent information is now required in many countries, and presenting the right information in the right way may stimulate important behavioral changes that can reduce smoking prevalence and thus save lives. Ensuring accurate understanding of constituents may also fulfill ethical and legal mandates to inform people of what they are consuming when they smoke cigarettes. Behavioral science is well-poised to address these important research opportunities.

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Compliance with ethical standards

Conflicts of interest Jennifer C. Morgan, M. Justin Byron, Sabeeh A. Baig, Irina Stepanov, and Noel T. Brewer declare that they have no conflict of interest.

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