Published in final edited form as:

Drug Alcohol Depend. 2012 July 1; 124(1-2): 1–10. doi:10.1016/j.drugalcdep.2012.01.012.

Role of Cigarette Sensory Cues in Modifying Puffing Topography

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Abstract

Background—Human puffing topography promotes tobacco dependence by ensuring nicotine delivery, but the factors that determine puffing behavior are not well explained by existing models. Chemosensory cues generated by variations in cigarette product design features may serve as conditioned cues to allow the smoker to optimize nicotine delivery by adjusting puffing topography. Internal tobacco industry research documents were reviewed to understand the influence of sensory cues on puffing topography, and to examine how the tobacco industry has designed cigarettes, including modified risk tobacco products (MRTPs), to enhance puffing behavior to optimize nicotine delivery and product acceptability.

Methods—Relevant internal tobacco industry documents were identified using systematic searching with key search terms and phrases, and then snowball sampling method was applied to establish further search terms.

Results—Modern cigarettes are designed by cigarette manufacturers to provide sensory characteristics that not only maintain appeal, but provide cues which inform puffing intensity. Alterations in the chemosensory cues provided in tobacco smoke play an important role in modifying smoking behavior independently of the central effects of nicotine.

Conclusions—An associative learning model is proposed to explain the influence of chemosensory cues on variation in puffing topography. These cues are delivered via tobacco smoke and are moderated by design features and additives used in cigarettes. The implications for regulation of design features of modified risk tobacco products, which may act to promote intensive puffing while lowering risk perceptions, are discussed.

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Contributors

Authors Rees and Kreslake conceived the study, conducted document searches and manuscript preparation. Ferris Wayne conducted document searches and manuscript preparation. O'Connor, Cummings and Connolly contributed to refinement of aims and manuscript preparation. All authors contributed to and have approved the final manuscript.

Conflict of Interest

KMC has served in the past and continues to serve as a paid expert witness for plaintiffs in litigation against the tobacco industry. No other financial disclosures or conflicts of interest were reported by the authors of this paper.

Keywords

Tobacco; puffing topography; cue reactivity; product design; nicotine

1. Introduction

Cigarette puffing is a complex behavior which ensures delivery of nicotine to the smoker, thus promoting tobacco dependence. Puffing topography refers to an individual's per-cigarette puffing profile which consists of number of puffs, puff volume, puff duration, puff velocity, and inter-puff interval (Marian et al., 2009). Together, puffing topography and other smoking behaviors (including the number and timing of cigarettes smoked per day, the length of cigarette smoked, and blocking of ventilation holes) influence nicotine dosing as well as exposure toxic cigarette smoke constituents: more intensive puffing can increase per volume yields of smoke constituents as well as produce a greater volume of smoke (e.g., Benowitz, 2001; Djordjevic et al., 2000; Hammond et al., 2005; Strasser et al., 2006, 2007). Smokers modify their puffing topography to influence nicotine delivery, thus optimizing nicotine plasma levels and nicotine reward (e.g., Griffiths and Henningfield, 1982; Hasenfratz et al., 1993; Herning et al., 1985; Scherer, 1999). Indeed, puffing topography varies through the course of a cigarette, by time of day, and according to individual physiological differences or needs (Collins et al., 2010; Gust et al., 1983; Guyatt et al., 1989; Kolonen et al., 1992). Cigarette design features also influence puffing topography. For example, cigarettes designed to produce low tar or nicotine yields, which tend to have high filter ventilation, promote intensive "compensatory" smoking (Benowitz, 2001; Hammond et al., 2006; Kozlowski and O Connor, 2002; Scherer, 1999; Strasser et al., 2007). However, it is not known whether other cigarette design features, including additives that alter chemosensory perceptions, also influence smoking behavior.

While smoking behavior has long been assumed to be regulated by circulating blood nicotine levels, other factors besides nicotine may contribute to puffing topography. A widely accepted model of smoking behavior, the nicotine titration model, proposes that smoking behavior must be modified to ensure delivery of a sufficient dose of nicotine on a puff by puff basis to provide the pharmacologically derived satisfaction and reinforcement desired by the smoker, and it must also be capable of providing sufficient total dosing to enable the smoker to maintain dependence and avoid withdrawal symptoms (Jaffe, 1990). Implicit in the nicotine titration model is the role of interoceptive feedback provided by changing plasma nicotine levels. In this model, puffing topography may be seen as a motivational response to the need to maintain nicotine reward and/or avoid withdrawal. However, nicotine may not reach the brain for some 10 – 20 seconds after a puff is completed, and peak nicotine levels may not occur until after smoking is complete (Benowitz et al., 2009), and therefore CNS nicotine effects cannot provide cues to guide a smoker's puff-by-puff behavior. This may require consideration of an alternative mechanism to explain variations in individual puffing behavior.

A growing body of evidence has suggested that sensory stimuli associated with smoking play a role in modulation of smoking behavior, independent of the central effects of nicotine. Rose and colleagues have suggested that so-called non-nicotine effects, which provide both sensory stimulation and other pharmacological influences, may directly or indirectly reinforce smoking behavior (Rose, 2006). Sensory factors have been shown to influence smoking satisfaction in highly dependent smokers, based upon more positive ratings of de-nicotinized cigarettes by smokers with greater tobacco dependence (Rose et al., 2000; Rose et al., 1993). These findings highlight the influence of sensory cues in the determination of smoking satisfaction (Rose and Behm, 2004), psychological reward

(Brauer et al., 2001), and craving reduction (Levin, et al 1993). Smoker perceptions of a “lighter” feel and taste of the smoke from highly ventilated cigarettes may also be an important factor in the higher acceptability of those products (Borland et al., 2004; Kozlowski and O Connor, 2002; Shiffman et al., 2001).

Theories of addictive behavior that employ principles of associative learning describe an important role for the sensory cues that are contiguous with drug administration and reward (West, 2006). Cues or conditioned stimuli (CSs) that are repeatedly paired with nicotine’s unconditioned stimulus (UCS) effects can acquire “incentive salience,” a motivationally significant state that may influence smoking-related behaviors (e.g., Robinson and Berridge, 2003). A broad literature on smoking cue reactivity has shown that external smoking cues (such as visual representations of smoking paraphernalia) produce conditioned responses (CRs) including smoking-related urges and behaviors (Sayette et al., 2010).

The influence of cigarette product design on smoking behaviors has been extensively investigated by the tobacco industry, and a broad base of research is available for analysis (Wayne and Connolly, 2009). Design modifications which produce specific sensory characteristics are used by manufacturers to establish brand and sub brand identity and enhance product consumer appeal (Carpenter et al, 2007). This study will review evidence obtained from previously secret, but now publicly available, internal tobacco industry documents to understand: i) the influence of sensory cues on puffing topography, and ii) how tobacco manufacturers manipulate puffing topography by modifying tobacco product design and emissions. A final aim is to: iii) examine tobacco industry strategies to design new consumer acceptable tobacco products, including modified risk tobacco products (MRTPs), using design features which alter sensory characteristics and thus puffing topography.

2. Methods

A snowball sampling method was used to conduct web-based, full text searches of the current collection of millions of internal tobacco company business records made publicly available through state litigation and the 1998 Master Settlement Agreement. The databases used in this study were the Legacy Tobacco Documents Library (www.legacy.library.ucsf.edu) and Tobacco Documents Online (www.tobaccodocuments.org).

A set of relevant documents was identified by expanding initial searches of general keywords and related synonyms. Documents were chosen based on their relevance in three major categories: (a) research on the relationship between sensory cues and puffing topography; (b) research on sensory characteristics and smoking behavior with specific cigarette products; and (c) research on puffing topography in relation to product development, especially with respect to low yield and modified risk products (MRTPs). Recurring authors, projects, and research proposals were identified when possible in order to discover further avenues for study. A total of 5,932 documents were produced by initial searches. Initial keywords included combinations of general phrases (e.g., “sensory response” and nicotine and “smoking behavior” [759 documents]; topography and perception and additive [568 documents]), with increasing specificity as targeted search processes were developed (e.g., “air dilution” and filtration and “sensory perception” [294 documents]; “puff volume” and “t/n ratio” and “sensory perception” [74 documents]). Based on their ability to directly inform the research questions, the results were narrowed into a final set of approximately 450 documents gathered from the major U.S. tobacco manufacturers (Philip Morris (PM), R.J. Reynolds Tobacco Company (RJR), Brown &

Williamson (BW), British American Tobacco (BAT) and Lorillard (LOR) 42 of which, ranging in date from 1984 to 2004, are cited in this paper.

3. Results

3.1 Effects of Sensory Cues on Topography

Multiple factors associated with variations in puffing topography were identified by tobacco industry scientists, with special attention paid to the influence of various product design features on sensory responses of nerves of the head, neck and lung. In 1994, BAT scientists "emphasized the point that perceived sensory responses cannot simply be related to smoke deliveries obtained under standard machine smoked conditions" (British American Tobacco, 1994). A 2003 tobacco industry report entitled *Influence of Cigarette Design on Human Smoking Behaviour and Sensory Responses* summarized the industry's explanation of puffing topography as a function of product design features (British American Tobacco, 2003). R.J.R.'s Nicotine RSM [Response Surface Methodology] Study attempted to understand the combined effect of three design variables (nicotine, tar, and resistance to draw) on taste, satisfaction, and acceptance (R.J. Reynolds, 1991a), in order to create definitions of optimal combinations of each of these elements. RJR scientists concluded that puffing topography differed between smokers of brands manufactured by different companies, and labeled the phenomenon a "franchise effect." An internal communication stated: "Since Winston and 'tar' yields, smokers who smoke these different cigarettes must use sensory clues [sic] not related to either FTC nicotine or FTC 'tar' to adjust their smoking behavior." (R.J. Reynolds, 1994a)

3.2 Influence of Product Design Changes on Sensory Responses

Internal investigations of variations on low tar cigarette design demonstrated that sensory cues influence puffing topography and nicotine delivery, which industry scientists presumed was mediated by product acceptability. RJR's 1989 Project XGT study on prototype cigarettes with lower tar to nicotine ratios compared with standard control cigarettes (Marlboro Light 85mm), revealed that fewer puffs were taken on the prototype, despite expectations that puff count and total puff volume would increase in a lower tar cigarette. The researchers speculated that subjects found the test cigarette, compared to the control, to be harsher, stronger, and "less palatable and reduced the number of puffs taken on these cigarettes simply because they did not enjoy smoking them as much as the [control]" (Robinson et al., 1992a). A 1994 internal study compared the influence of experimental prototypes of RJR's electrically-heated cigarette, Premier, on puffing topography and serum nicotine levels. The Premier study prototypes included a version with a carbon filter and a carbon filter plus potassium carbonate (designed to increase 'mouthfeel,' an important tactile cue), and these were compared with a Camel Lights control cigarette. While the carbon filter prototype produced similar puffing topography and nicotine serum concentrations compared with the control, the addition of potassium carbonate resulted in greater interpuff interval, lower puff volume and shorter puff duration, and lowered serum nicotine (R.J. Reynolds, 1994b). The addition of potassium carbonate, rather than enhancing desirable sensory attributes as anticipated, increased negative sensory attribute ratings (i.e., high throat and chest impact, lower smoothness/more harshness), which industry scientists concluded was responsible for the observed changes in topography and subsequent serum nicotine. Similar results were obtained in other studies of cigarette and MRTP prototypes designed to vary according to "impact" (a sensory response produced by stimulation of pain nociceptors): products with more harshness, less smoothness, and higher impact were not puffed as intensively as a control product with more positive sensory attribute ratings (R.J. Reynolds, 1994c). These findings demonstrate the influence of product design on sensory perceptions, which will be considered in more detail according to three major design feature modifiers used by cigarette manufacturers: harshness-smoothness balance, non-irritant sensory responses, and resistance to draw.

3.2.1 Harshness-Smoothness Balance—Nicotine (and certain other smoke constituents) produces harshness, which is associated with greater irritation, "impact" of inhalation, and flavor strength. Nevertheless, the ability to detect the presence of nicotine in smoke may be enhanced or masked by other smoke constituents. Here it is important to distinguish the role of sensory or other cues from nicotine delivery: "the sensory part is not the total exposure or how much was in the cigarette, or how much came out of the cigarette. Rather it is the dose. How much you got from the smoke to where the smoker could feel it" (R.J. Reynolds, 1992). The role of product design is to provide the smoker with both delivery as well as adequate perception of delivery. Thus:

> The factors that will ultimately account for differences in the acceptance or rejection of our cigarettes lie not in the quantity of nicotine per cigarette or per puff but in other aspects of the chemistry of mainstream smoke that translate into sensory effects. That is, while nicotine does have clear sensory effects, it is the other compounds in smoke that modulate how the smoker delivers nicotine to himself. (Walker, 1990a, p.1)

Brown and Williamson also observed that among conventional cigarettes puff-by-puff impressions of impact, irritation and flavor intensity increased during the act of smoking, while ratings for acceptability and flavor quality increased initially, reached a plateau and then declined in later puffs. The behavioral response to these impressions was that smokers tended to decrease their puff volumes with succeeding puffs. Proposed mechanisms for the changes in perception throughout the smoking of the cigarette included sensitization of the sensory system, increases in smoke concentration in later puffs, and changes in smoke composition in later puffs (for example, increased smoke pH or changes in tar/ nicotine ratio) (Brown and Williamson, 1992).

When PM conducted research comparing puffing responses to ultra-low tar versus denicotinized ("Next") cigarettes, they found that: "With respect to puff volume and number of puffs it seems that the ultra-light cigarettes but not Next were oversmoked" (Baldinger et al., 1993; Hasenfratz et al., 1993). Similarly, in a published study, Robinson and colleagues indicated no significant differences in the way the subjects puffed and inhaled a cigarette of 0.6-mg nicotine yield, and a test cigarette of only 0.06 mg nicotine but with similar amounts of tar and CO (Robinson et al., 1992b). The conclusion was that, with respect to compensatory smoking behavior, "tar dependent sensory cues may thus play an important role in the regulation of smoke intake and the modulation of craving" (Baldinger et al., 1993). These findings are now well supported in the literature (Rose, 2006).

A similar conclusion can be drawn at the opposite end of the nicotine delivery spectrum – products engineered to enhance smoothness, in which irritation and impact is lower. For example, BAT observed with respect to the inclusion of the genetically modified, high-nicotine Y1 tobacco that it provided "a greater pharmacological response than their impact might lead the smoker to expect. This may be due to relative reductions in an irritation cue" (British American Tobacco, 1990). Thus, smokers were unprepared for the nicotine dose because the cues they received were interpreted as low nicotine availability which prompted over-dosing.

A number of internal studies have sought ways to mimic or replace nicotine (British American Tobacco, 2001). Studies funded by BAT sought to determine the point in the throat at which impact receptors are localized. By developing a "map" of such receptors in the upper airways, it was hoped that nicotine alkaloids which are capable of binding to and activating these receptors could be identified. “Thus the studies are aimed at identifying other materials (apart from nicotine) capable of eliciting the impact sensation, with a view to developing the ability to modify the quantity and quality of the impact sensation through additives with the ability to activate the same receptor/nerve system as nicotine itself” (Brown and Williamson, 1992). These and similar studies (Vagg and Chapman, 2005), suggest the importance of providing smokers with perception of nicotine dose in the absence of a central pharmacological effect. This sensory response may, in turn, provide a critical cue for the tailoring of the puffing response to allow optimal nicotine dosing.

3.2.2 Non-Irritant Sensory Responses—BAT researchers conducted studies on “smoking dynamics,” a term for the relationship between smoker and cigarette (Ayres and Greig, 1984; Brown and Williamson, 1985). The goal of this research was to identify the factors in smoking which determined behavioral responses, including puffing and inhalation patterns. As one study noted, the smoker “seems to be able to adjust smoking behavior almost instantaneously while puffing” (Ayya et al., 1995). The authors determined that sensory cues detected during the puffing process, including tactile cues of body and mouthful (the sensory feeling of smoke entering and occupying the mouth), were a controlling factor in the determination of the duration and volume of a given puff (Ayya et al., 1995). The research found that smoke from cigarettes with high body and mouthful was inhaled in smaller volumes and over shorter periods of time than smoke from cigarettes with low body and mouthful. Table 1 displays a summary and definitions of cigarette design features and sensory characteristics identified by industry research as an influence on puffing topography.

Likewise, studies were conducted at RJR to identify the physical and chemical design factors which determine “how the smoker delivers nicotine to himself” (Walker, 1990a). Among the factors considered were: the physical nature of the smoke (particle size, amount of gas phase), key components in particulate matter, and characteristics of the pressure drop. Design factors that influenced perception of smoke in the mouth included differences in processing, additives, and physical product characteristics. For example, reducing the density of the tobacco rod increased mouthful, as did use of ammoniated tobacco (R.J. Reynolds, 1991b). The hydrophobic compound, n-hexadecane, enhanced body and mouthful without affecting impact or irritation, while a hydrophylic compound had no effect on either response (Bevan and Shepperd, 1992).

One interesting question raised with respect to feedback was whether there was a “window” during which a smoker adjusts puffing topography, and if so, how long this window remains open. A 1984 BAT review of different studies in this area observed that sensory feedback appeared to proceed in stages. “It would appear that in the first part of the cigarette perceptions of mechanics play a key role, while in the second part, delivery is most important, and in the last part of the cigarette, perceptions of irritation are most influential” (British American Tobacco, 1984). The authors noted that, in contrast to puffing pattern, most smokers maintained the same inhalation pattern that was established with their baseline cigarette, even when offered markedly different cigarettes, although puffing pattern (e.g., frequency) might be altered.

Industry researchers have also considered a range of potential factors to explain the typical decline in puff volume and duration during the course of consuming a single cigarette. In 1993, BAT scientists dismissed a number of popular explanations of inter-cigarette changes in puffing topography in favor of the role of sensory responses. A study of visual cues, including smoker awareness of the relative proximity of the burning coal to the end of the cigarette, suggested a low influence on puffing behavior. Nicotine satiation was posited as another factor; the smoker “initially takes large puffs to increase nicotine intake, and subsequently backs of [sic] as nicotine satiation occurs” (Whitehead, 1994). Puff volumes were shown to relate to increases in filter resistance to draw as the cigarette is consumed. Finally, changes in mouth sensations and sensory effects (i.e., mouthful, irritation, impact) were postulated to influence intensity of puffing behavior (Whitehead, 1994).

3.2.3 Resistance to Draw and Perception of Draw Effort—

Increasing the effort required to obtain a drug can reduce and ultimately lead to discontinuation of drug self-administration. Indeed, reducing nicotine appears not only to make it more difficult for the user to self-administer desired levels but may also reduce the satisfaction of smoking (Goldberg et al., 1981). An RJR document observed the difficulty for smokers “attempting to move from a 3–6 mg [tar] product to a 1–2 mg product” noting that these smokers tended to be most dissatisfied by decline in perceived chemosensory impact, probably caused by lowered free nicotine (Walker, 1992). Similarly, according to a set of one-on-one surveys with ultra-low tar smokers, the problem with the ultra-low tar cigarette was “a loss of satisfaction due to lower taste impact delivery” (Kay et al., 1993a). These and similar observations pointed to the conclusion that design – mediated sensory effects experienced during puffing, as opposed to measured tar and nicotine delivery, played the largest part in determining the acceptability of low and ultra-low delivery cigarettes.

Research was conducted on factors that influence perception of draw, defined as the amount of perceived effort needed to inhale smoke from the cigarette. BAT studied this phenomenon using pairs of cigarettes with different responsiveness to physical draw effort but equivalent machine yields. They found that the smoker’s perception of draw effort was not a function of actual physical draw effort, but rather, was an inverse perception of the physical fullness of the smoke in the mouth (defined by ratings of body and mouthful). Perceived draw effort was linked to smoker acceptability ratings. That is, product acceptance was defined for low tar cigarettes by the perceived fullness of smoke, and not just particular taste or quality perceptions (Ayya et al., 1995).

Perception of draw was identified not only as a key factor in consumer acceptance not only of ultra-low tar yield cigarettes, but also MRTPs with nonconventional designs:

> …evaluations of high technology cigarette prototypes have resulted in concerns relative to the subjects’ POD [perception of draw]. Specifically, subjects felt that the resistance was too high. Similar POD concerns were indicated in PREMIER studies. Unfortunately, we have little understanding of what drives these complaints (Kay et al., 1993a, p.3).

RJR also conducted research on cigarette design and perceptions of draw (Hayes et al., 1991; Walker, 1990a, 1990b, 1992, 1993). Additives and blend changes were shown to alter perception of draw (Kay and Morgan, 1994). Mainstream smoke constituents tar, nicotine, formaldehyde, acetaldehyde, acrolein, acetone, ammonia, were found to be positively related to perception of draw (Kay et al., 1993a). When both chemical and physical factors were considered, the mainstream constituent yields were more closely linked with perception of draw than the physical factor resistance to draw (Kay et al., 1993a). Taken together, these findings suggest that smokers rely on chemical signals received in the mouth and upper respiratory tract to feel that they are not being forced to work too hard to achieve a sufficient volume of smoke. Without these signals, a smoker may puff harder regardless of how much nicotine or other smoke has been delivered (Walker, 1992).

3.3 Applications of Industry Research in Targeting of Consumer Preferences

Tobacco manufacturers used their developing knowledge of the influence of product sensory characteristics on puffing topography to enhance the consumer acceptability of cigarettes. In particular, tobacco industry scientists considered the influence of design features on sensory attributes (Brown and Williamson, 1996; Pritchard and Robinson, 1994). A 1990 internal review concluded that the physiological responses of smokers to cigarettes were valuable indicators of acceptable sensory characteristics, and placed a particular emphasis on measuring puff profiles, amount of smoke “wasted” after puffing, and characteristics of the first inhalation after the puff (Walker, 1990a). Figure 1 shows an industry model of the relationship between these factors (implying a feedback loop between sensory perceptions, neural effects and puffing topography), and their implications for the enhancement of product consumer acceptability (R.J. Reynolds, 1990a).

This model guided further research on the design and sensory effects of low yield cigarettes, which almost universally use high filter ventilation. While tobacco companies were aware that higher filter ventilation produced more intensive puffing, they understood that it reduced desirable sensory characteristics. In order to create highly ventilated products that had acceptable sensory characteristics for smokers, other cigarette construction parameters were investigated, and the influence of these design modifications on puffing topography was examined (R.J. Reynolds, 1985). In 1994, BAT scientists noted:

> The observation that the duration of the puff and subsequently puff volume is regulated by a control mechanism activated in the mouth during the puff (possibly mouthful) could be important when one considers low delivery products. Generally low and ultra low tar products are deficient in most sensory attributes [e.g., mouthful, impact and flavor amplitude].
>
> One can enhance the impact and flavor sensations by [using] higher nicotine tobaccos [blend], flavor additives, alkaline additive [additives] etc. … However, if the ‘enhanced’ products remain deficient in mouthful the smoker would prolong the duration of the puff, increase puff volume and obtain high levels of perceived inhalation strength. Consequently, the smoker may rate the cigarette as being unbalanced or in extreme cases far too high in inhalation strength characteristics. This reinforces the view that mouthful enhancement must be addressed in the pursuit of methods for enhancing perceived strength characteristics of low delivery products (British American Tobacco, 1994, p.118).

Brand development and refinement was the ultimate motivation behind the tobacco industry’s attempts to understand the relationship between product design and properties of smoke, and responses to sensory cues and puffing topography. For example, research initiatives were in place at companies such as RJR to determine how puffing topography and sensory perception enhance product acceptability, with direct implications for changes to brand design (R.J. Reynolds, 1990b). Optimal combinations of design features, including nicotine/tar ratio and draw effort, were defined for products such as Winston, Camel, Dakota and Vantage, as well as in new brands, in order to “maximize acceptance among one or more smoker groups/mindsets.”

RJR’s HSB [Human Smoking Behavior] program was the result of a merging of methodologies between Research and Development (R & D) and Marketing Research (MR) departments (R.J. Reynolds, 1990c). The R & D department had developed a laboratory method to measure physical properties of an individual’s puffing topography, as well as a way to estimate smoke constituent yields based on individual topography. Meanwhile, MR developed a clustering methodology that allowed grouping of smokers according to what they perceived as an “ideal” cigarette based on preferred cigarette sensory characteristics (Figure 2).

In 1991, RJR reported data from their Four-City Study, whose purpose was to confirm whether smokers (N = 1319) could be divided into subgroups based on their perceptions of an ideal cigarette, and whether smoking behavior was associated with their ideal ratings (Kay et al., 1993b; R.J. Reynolds, 1991c). The study also attempted to determine whether participants in each cluster responded to changes in cigarette design in similar fashion. A third aim of the study was to "determine if there were any psychological/sociological or demographic descriptors of product-want clusters to aid marketing to these clusters." Participants were assigned to clusters based upon their ideal cigarette sensory attributes: harshness, smoothness, strength and tobacco taste (Figure 2). According to these groupings, Cluster 1 smokers (n=394; 29.9%) desire smoothness along with moderate tobacco taste and low impact; Cluster 2 (n=301; 22.8%) want a high degree of smoothness, strength and tobacco taste; Cluster 3 (n=185; 14.0%) want a low impact product with moderate tobacco taste; and Cluster 4 (n=439; 33.3%) desire a high impact, with smoothness and tobacco taste. Participants in the four clusters responded to product changes differently and varied significantly in measures of puffing topography (R.J. Reynolds, 1991c) (see Figure 3).

The HSB program demonstrated differences in individual smoking profile, based upon preference for cigarette sensory qualities. Changes in puffing topography were shown to be related to changes in sensory perception: puff volume changes were associated with strength (of sensory impact from nicotine); changes in puff duration were related to harshness of smoke; and changes in puff frequency were related to satisfaction. The direction of change was determined by group identification based on rated preferences of an "ideal" cigarette. For example, smokers who desired a greater nicotine effect took larger puffs, those who wanted nicotine strength without harshness took slower, longer puffs than those who desired higher strength plus harshness, and smokers who wanted smoothness with less strength and harshness took shorter and smaller puffs.

3.4 Development and Evaluation of Modified Risk Tobacco Products

The development of modified risk tobacco products required balancing the need to lower smoke constituent delivery while maintaining sensory characteristics that were acceptable to consumers. Modified risk tobacco products such as Accord and Eclipse and Marlboro UltraSmooth performed poorly in the market due to low acceptability among consumers (Wayne and Connolly, 2009). The relationship between sensory response and puffing topography gained new importance as research was conducted to address problems with consumer acceptability of reduced exposure products.

Tobacco companies considered sensory cues and puffing topography as important determinants of exposure, describing smoking as "a lot more than nicotine-taking" and as recently as 2001, identified control of puffing topography as critical in efforts to develop reduced risk products (Philip Morris, 2001a, 2001b, 2001c). During the past decade, PM suggested that research on the relative influence of nicotine and non-nicotine design features on smoking behavior was "critical work" for the future (Philip Morris, 2002). In 2004, PM conducted research to determine the role that sensory responses originating in the back of the throat, trachea, or lungs play in mediating puffing topography. These sensations were termed the "stop signal." The company was interested in identifying the source of the sensation, the mechanism involved in its creation, and its effect of perception of the sensory effect on inhalation and exhalation patterns. The "stop signal" was identified as important for improvement of MRTP subjective ratings (Philip Morris, 2004).

Other industry work combined puffing topography and acceptability measures in the evaluation of MRTP prototypes. RJR collected data on puffing topography among smokers with either a full-flavor or light cigarette as their usual brand, and compared it to data collected while using a cigarette fuelled by a carbon element in which tobacco is heated but not burned. Sensory ratings, which were lower for an Eclipse prototype than for subjects conventional cigarette brand, were associated with lower nicotine exposure as measured by salivary cotinine (R.J. Reynolds, 1997). The company conducted a similar study on PM's electrically heated cigarette (Accord) and found that less intensive puffing topography (i.e., lower volume and shorter puffs) was associated with lower serum nicotine level (R.J. Reynolds, 1994b, 1994d). Changes in puffing behavior following switching to a MRTP in both studies were attributed to changes in acceptance and satisfaction scores. Sensory perceptions such as higher harshness, lower smoothness and tobacco taste were cited as key factors contributing to altered inhalation patterns, which prompted PM to improve MRTP sensory characteristics by modifying flavorants and other additives in MRTP cigarettes (Philip Morris, 2002).

4. Discussion

Data from internal tobacco industry research show that puffing topography is influenced by sensory cues associated with nicotine delivery. Tobacco industry scientists have identified relationships between product design characteristics, chemosensory effects, and puffing topography. Chemosensory cues derived from smoking, such as harshness, impact, taste, and mouth feel, provide cues for nicotine delivery, and play a role in determining puffing behavior. This may occur as sensory stimuli that accompany puffing provide more or less instantaneous feedback on how much nicotine is available in the smoke, and thus may inform the smoker on how to adjust puffing behavior so as to gain or maintain an optimal dose. Design features that were found to play a role in the modification of chemosensory response included resistance to draw, perceptions of harshness-smoothness (mouthfeel), and other non-irritant sensory responses such as smoke body (mouthful). Tobacco manufacturers have used this information to modify cigarette design features to optimize nicotine dosing while maintaining sensory appeal.

Sensory cues, which can be highly characteristic for individual tobacco products, reliably predict the onset of nicotine reinforcement, thus providing a basis for a learned association between these events. A working model of puffing topography, adapted from West (2006), using principles of incentive sensitization theory (Robinson and Berridge, 2003), is proposed. Cigarette brand-specific chemosensory cues (conditioned stimulus, CS), when paired with the unconditioned effect of nicotine (UCS), may acquire “incentive salience” which influences puffing behaviors (Figure 4). The information provided by sensory cues may allow tailoring of the puffing response to moderate nicotine yield per puff, as well as the total amount of nicotine generated per cigarette and inhaled via smoke. Modifying the puffing response may qualitatively change sensory cues, as well as the attendant nicotine delivery. In this way, the puffing response may be seen as a self-correcting feedback mechanism which responds to perceived variations in sensory information, for optimization of nicotine delivery and reward. Variation in puffing topography was observed in response to three broad categories of chemosensory cues: mouth cues related to tar, impact cues related to nicotine, and cues provided by mechanical resistance to draw. This suggests that different cue types could become conditioned to nicotine's effects, and is consistent with the broader cue reactivity literature which shows that multiple types of cue can elicit smoking-related responses (e.g., Conklin, 2006). The data also suggest that specific sensory preferences, which distinguish sub types of smokers, are associated with variations in puffing topography.

The implications of these findings for understanding consumer acceptability of tobacco products (and the broader construct of abuse liability), are particularly striking. Sensory response, smoking style and nicotine reward may interact in a complex manner to influence product acceptability. The tobacco industry has invested considerable resources in developing products which optimize nicotine delivery for the smoker and maintain or enhance desirable chemosensory effects, while reducing delivery of other toxic smoke constituents. Previous research has reported industry manipulation of product sensory characteristics to enhance acceptability among smoker subtypes (Carpenter et al., 2007). Separately, independent researchers have shown that non-nicotine sensory effects, including modifications to filter ventilation influence subjective responses and smoking topography (Benowitz, 2001; Hammond et al., 2006; Kozlowski and O Connor, 2002; Strasser et al., 2007). The present data extend these findings by broadening our understanding of the influence of chemosensory cues, derived from product design manipulations, on puffing topography. Indeed, the industry's success in varying product sensory characteristics may have implications beyond enhancement of product acceptability.

The model of puffing topography proposed here suggests that altering or removing familiar sensory cues, such as by switching to a different brand, may interrupt the finely tuned smoking behavior that optimizes nicotine dosing. The general failure of cigarette MRTPs to achieve commercial success may be due, in part, to disruption of the chemosensory cue-nicotine dosing feedback loop. Indeed, a number of studies outside of industry research have shown changes in puffing topography when smokers are switched to cigarettes with similar machine-measured nicotine yields, but have different chemosensory properties (Rees et al., 2008; Kozlowski and O Connor, 2002). Likewise, the limited commercial appeal of denicotinized cigarettes such as Quest may be due to disruptions to the established chemosensory cue-nicotine dosing contingency. The present data also have implications for further research on tobacco cue reactivity, by identifying a previously unrecognized role for product design as a source of highly specialized chemosensory cues for nicotine delivery. The highly specific nature of the sensory cues associated with individual cigarette products may contribute to the abuse liability of those individual products, insofar as associative mechanisms underlie the puffing topography that optimizes nicotine dosing.

Certain limitations in the methods employed in this research are acknowledged. First, the tobacco industry research on which this evidence is based was not externally peer reviewed, and was conducted to promote commercial interests. Nevertheless, industry studies reported here have been evaluated for methodological rigor, and, taken in context, can be considered a valid source of scientific information. Second, the present analysis was limited to publicly available industry documents which may comprise an incomplete picture of internal research and findings. In particular, the limited quantity of research available after 1997 may be indicative of a potential lack of accessibility to recent documents, rather than the absence of industry research during this period. Third, because industry research was designed primarily for the purpose of product development and enhancement of product acceptability, there is insufficient evidence to directly support causal, directional relationship between chemosensory response and puffing topography. Direct testing of human smoking is required to establish whether sensory cues inform resulting topography, through smoker adjustment of smoking behavior to perceived sensory attributes. Clearly, further research is required to understand the influence of diverse factors on puffing topography, and the conditions under which they become active. A comprehensive model of smoking behavior must therefore account for the role of multiple, diverse influences.

Improved understanding of the influence of cigarette design on smoker behavior has important implications for regulation of new tobacco products and those which meet criteria as modified risk tobacco products. The U.S. *Family Smoking Prevention and Tobacco Control Act* of 2009 provides the Food and Drug Administration (FDA) with regulatory authority for tobacco products designed, marketed, or perceived by consumers as capable of reducing exposure or harm. Modified risk tobacco products require evaluation to show that product claims or design features do not suggest lowered harm when none have been proven. The present findings suggest that measures of puffing topography must be understood in the context of product design features and the attendant chemosensory response. Product design features may enhance abuse liability by providing cues for optimizing puffing topography and nicotine dosing. One such design feature, filter ventilation, has been the subject of previous calls for a ban (Borland et al., 2004; Kozlowski and O Connor, 2002). It follows that assessment of new and modified tobacco products by the FDA must encompass design features and additives which influence tobacco product abuse liability.

Acknowledgments

Role of Funding Source

This work was funded by National Cancer Institute contract N01-PC-64402 and grant RO1-CA1-25224. The National Cancer Institute collaborated with the authors in study planning and in the decision to submit the paper for publication. All other aspects of this research, including data collection and manuscript preparation, were conducted independently.

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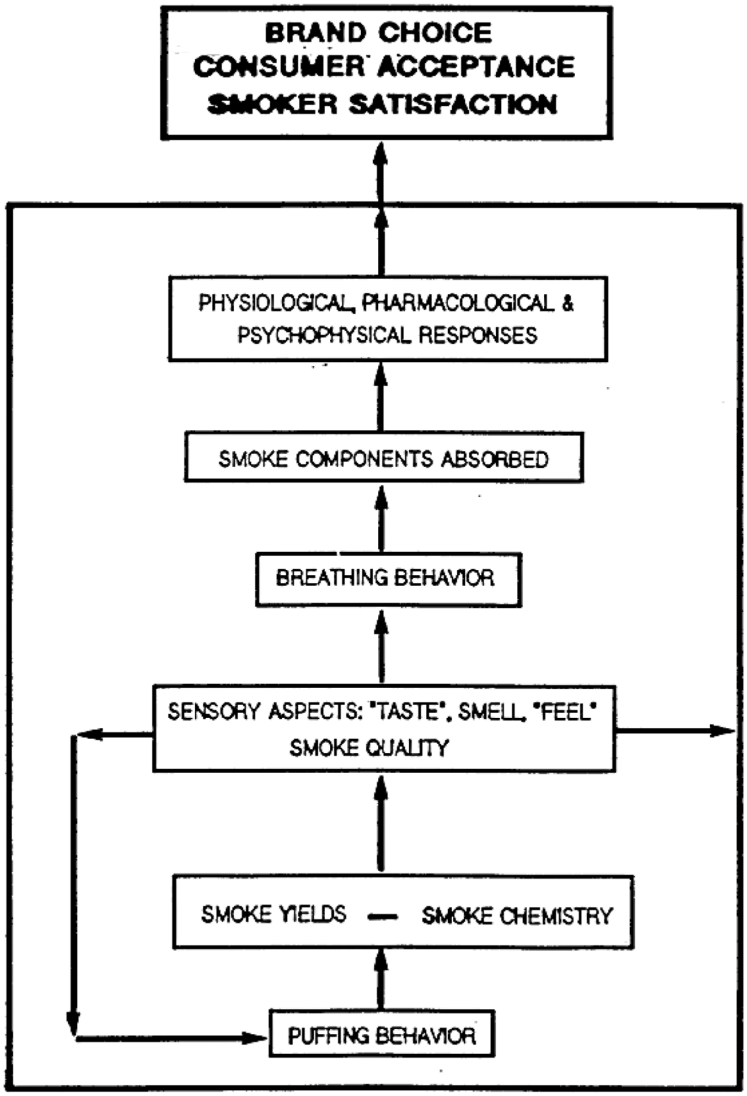


Figure 1.

Industry model of the influence of sensory cues on puffing behavior (R.J. Reynolds, 1990a)

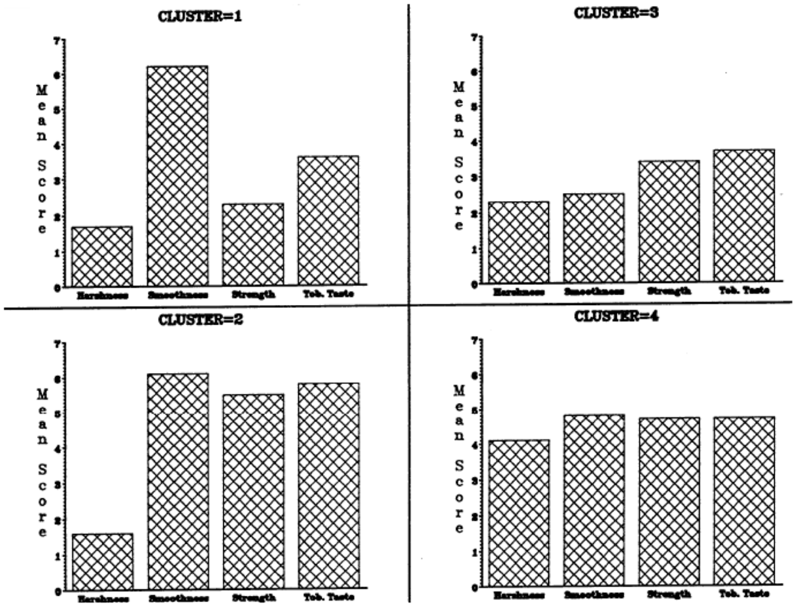
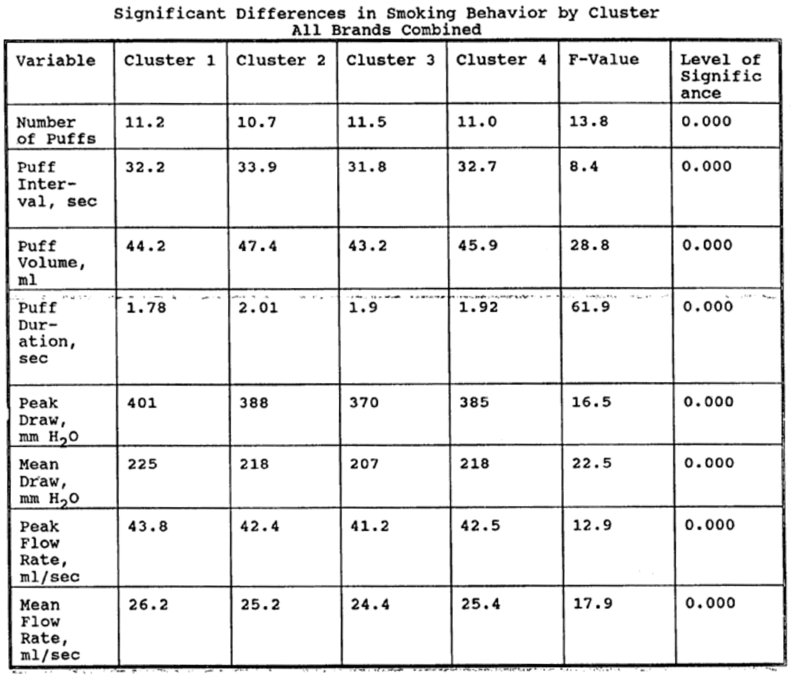


Figure 2.

Smoker sensory preference sub-type clusters, based on response to harshness, smoothness, strength and tobacco taste (R.J. Reynolds, 1991c)



Significant Differences in Smoking Behavior by Cluster
All Brands Combined

Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4	F-Value	Level of Significance
Number of Puffs	11.2	10.7	11.5	11.0	13.8	0.000
Puff Interval, sec	32.2	33.9	31.8	32.7	8.4	0.000
Puff Volume, ml	44.2	47.4	43.2	45.9	28.8	0.000
Puff Duration, sec	1.78	2.01	1.9	1.92	61.9	0.000
Peak Draw, mm H_2O	401	388	370	385	16.5	0.000
Mean Draw, mm H_2O	225	218	207	218	22.5	0.000
Peak Flow Rate, ml/sec	43.8	42.4	41.2	42.5	12.9	0.000
Mean Flow Rate, ml/sec	26.2	25.2	24.4	25.4	17.9	0.000

Figure 3.

Industry demonstration of variations in puffing topography by sensory preference sub-type (R.J. Reynolds, 1991c)

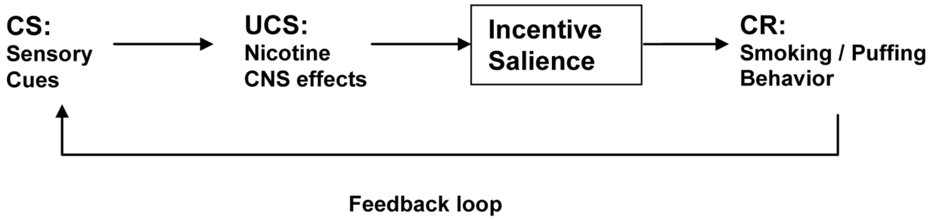


Figure 4.
Model of incentive salience of cigarette sensory cues for puffing topography
CS: Conditioned stimulus; UCS: Unconditioned stimulus; CR: Conditioned response

Table 1

Physical design features and chemosensory characteristics

Cigarette Design Features		
Filter design:	Ventilation	Vent holes strategically placed in the filter to allow entry and mixing of air with cigarette smoke. Enhances perceptions of smoothness. Reduces other sensory characteristics, such as taste.
	Resistance to draw	Physical resistance to the passage of air and/or smoke through the cigarette and into the mouth
	Carbon filter	Reduces particulate phase constituent yields and may enhance smoothness
Cigarette rod design:	Rod circumference	Tobacco rod circumference influences resistance to draw and burn temperature
	Tobacco blend	Proportions of Virginia, burley and oriental tobaccos, either air or flue cured, and intended to convey greater flavor characteristics or nicotine delivery
Smoke constituent delivery:	Nicotine delivery	Nicotine delivered via mainstream smoke to the smoker
	Tar delivery	Tar delivered via mainstream smoke to the smoker
	Gas phase constituents	Mainsteeam smoke constituents in gas phase at the time of delivery, including nicotine, volatile organic, carbonyl and phenolic compounds
	Particle size	Smaller tobacco smoke particles enhance perceptions of smoke smoothness and reduce perceptions of draw effort and risk
Additives:	Ammoniation	A strategy to modify pH which increases the proportion of unprotonated to protonated nicotine
	n-hexadecane	Alkane hydrocarbon used to enhance mouthful and body
	potassium carbonate	Alkaline salt compound added to tobacco to enhance mouthful/ mouthfeel
Sensory Characteristics		
Draw effort:	Draw effort/ Perception of draw	Perceived amount of effort required to draw a satisfactory amount of smoke from the lit cigarette into the mouth
Harshness-smoothness balance:	Harshness	Sensory characteristics with higher impact and irritation effects
	Smoothness	Sensory characteristics with lower impact and irritation effects
	Impact (throat/chest)	A sudden, sharp, but short-lived sensation felt upon the back of the throat upon inhalation (BAT, 570354096/4354)
	Irritation	A more persistent sensation than impact, in which the intensity of prickling, tingling, itching and similar sensations build up and slowly fade away (BAT, 570354096/4354)
Non-irritant sensory And subjective responses:	Pleasure	A term generally understood by smokers to imply nicotine effects; the subjective interpretation of nicotine reward or reinforcement
	Satisfaction	See pleasure
	Flavor	A combination of perceived sensory characteristics taste, odor, and touch
	Strength	Magnitude of flavor characteristic
	Acceptance	"Perceived fullness of smoke, and not just particular taste or quality perceptions." Basis for consumer product preference.
	Palatability	The presence or absence of desirable flavor characteristics, including flavor strength and harshness-smoothness balance
	Mouthful	"The impression of volume or amount of smoke entering the mouth and occupying the mouth during puff taking" (Ayya et al., 1995)
	Mouthfeel	See mouthful

Cigarette Design Features		
	Body	See mouthful