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# Regulation of Tobacco Smoke Intake with Paced Cigarette Presentation

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GRITZ, E R, J E ROSE AND M E JARVIK *Regulation of tobacco smoke intake with paced cigarette presentation* PHARMACOL BIOCHEM BEHAV **18**(3) 457–462, 1983 —Smoking behavior in response to an increased presentation of cigarettes was investigated to determine whether compensatory changes occurred in order to maintain a constant intake of tobacco smoke The lighting of each cigarette was paced at both twice and four times that of subjects' baseline smoking rates in a three condition repeated measures design for eight smokers Puff topography—number of puffs per cigarette, puff duration volume, peak flow and interpuff interval—was monitored continuously Results showed that subjects titrated smoke intake as summarized by three smoke compensation indices based on number of puffs, puff volume and puff duration Compensation was virtually complete in the double rate condition and substantial in the quadruple rate condition Results of this experiment do not support the view of a bimodal distribution of smokers, "compensators" and "noncompensators," since a continuous range of compensation ratios was obtained The measures of individual puff topography were only modestly correlated, and were generally highest for volume × duration Volume would appear to be the most accurate measure of tobacco product consumed

Cigarette smoking Tobacco Nicotine titration Compensation Puffing topography

A PROMINENT explanation of cigarette smoking proposes that smoking is maintained by the ingestion of pharmacologically active agents in tobacco, particularly nicotine [1, 12, 17] Contrasting hypotheses stress the importance of social and sensorimotor aspects of the habit [10, 11, 15] The principal strategy in evaluating the role of pharmacological variables in cigarette smoking has been to determine whether individuals regulate their intake of tobacco products when subjected to various manipulations Gritz *et al* [8], for example, presented smokers with half-length cigarettes, and found that subjects smoked more than when given full-length cigarettes, tending to maintain constant nicotine levels Jarvik *et al* [13], using half-, quarter-, and eighth-length cigarettes, also reported compensatory increases in puffing rate with the shortened cigarettes Ashton *et al* [2] compared smoking topographies when subjects were given either full-length, or two-thirds length cigarettes Number of cigarettes was held constant across conditions, and was equal to the number smoked in baseline for each subject Slight increases over expected puffing rate and nicotine delivery were observed with the two-thirds cigarettes, which indicated partial compensation Recently, Griffiths *et al* [6] determined that the number of puffs per "bout" varied inversely with interbout interval, when either was manipulated experimentally A common finding in all of these experiments was that subjects evidenced some compensatory efforts, but seldom changed their manner of smoking to fully regulate their intake Specifically, only slight increases in smoking occurred as compensation for reduced delivery from each cigarette

We undertook the present study to investigate smokers' compensatory responses to an increased presentation of cigarettes This was achieved by pacing the lighting of each cigarette at either twice or four times that of subjects' baseline smoking rates and determining whether subjects altered the way in which they smoked each cigarette in order to maintain a constant intake of tobacco smoke In order to assess these changes in smoking, we measured the detailed topography of subjects' smoking behavior Puff topography (number of puffs per cigarette, puff duration, volume, peak flow and interpuff interval) has been studied by several investigators in its relation to nicotine titration [3, 4, 9, 14, 16] Since none of the studies involving manipulations of cigarette length or rate of presentation have incorporated measures of actual smoke volume taken into the mouth per puff, however, we recorded this parameter as well as the other topographical variables Volume changes would appear to be a more valid index of smokers' efforts to regulate tobacco intake than, for instance, puff duration, because volume best reflects the quantity of smoke constituents ingested Our goal was to determine how well volume measurements correlated with other topographical characteristics, such as puff duration as duration may be more easily measured

TABLE 1

SMOKING CHARACTERISTICS OF SUBJECTS

| Subject No. | Age | No. Cigs Smoked/Day | Nic. Yield (FTC Method) | No. Cigs Smoked in Baseline |
|---|---|---|---|---|
| 1 | 37 | 40 | 1.4 | 4 |
| 2 | 28 | 20 | 1.3 | 4 |
| 3 | 38 | 20 | 1.4 | 4 |
| 4 | 35 | 30 | 0.8 | 4 |
| 5 | 30 | 30 | 1.1 | 3 |
| 6 | 20 | 10 | 1.1 | 6 |
| 7 | 28 | 40 | 1.1 | 4 |
| 8 | 28 | 30 | 0.7 | 4 |
| Mean | 30.5 | 27.5 | 1.1 | |
| ±s.d. | ±6.0 | ±10.4 | ±0.3 | |

## METHOD

*Subjects*

Eight male drug-free, non-psychotic inpatients being treated in a "resocialization program" at the Veterans Administration Medical Center Brentwood provided informed consent to serve as paid volunteer subjects. They ranged in age from 20 to 38 years (mean=30.5, s.d.=6.0) and smoked an average of 27.5 cigarettes per day (s.d.=10.4) with a mean nicotine yield (FTC method) of 1.1 mg/cigarette (s.d.=0.3). Table 1 provides individual subject data on these smoking characteristics.

*Equipment*

Smoking topography was continuously monitored with a specially designed cigarette holder subjects used to smoke each cigarette. The holder contained a thermistor sensor, operated in a self-heated mode to sense the flow of smoke. The thermistor was heated to approximately 200°C, by an electric current, and during each puff the flow of smoke instantaneously cooled the thermistor. This transient cooling changed the thermistor's electrical resistance which was measured and converted to a voltage signal by associated circuitry. Tar and nicotine residue was prevented from accumulating on the thermistor due to its high temperature. The system was calibrated initially by drawing air through the holder with a vacuum pump connected to an independent flow meter (Gilmont spherical float flowmeter). This calibration curve was used in the computer integration of flow signals to determine volume. A comparison of smoke with air calibration was performed by drawing a known volume (60 cc) of either smoke or air through the holder, using a syringe. Smoke tended to generate a slightly larger signal (approximately 10%) than air, probably due to a more efficient cooling of the thermistor produced by the particulate matter in smoke. The calibration also changed less than 10% across puffs of a cigarette. This small, consistent difference between air and smoke calibrations was judged to be inconsequential for the comparisons between conditions in the studies reported here.

*Data Analysis*

Puffs were recorded as analog signals on magnetic tape using an A. R. Vetter Model A recorder. Data were digitized using a PDP-12 computer at the UCLA Brain Research Institute, and then analyzed using the Statistical Analysis System and BMDP Statistical Software [5]. By visual analysis of the data, it was decided to count as puffs only those measured at intervals of greater than 2.5 seconds, that is, all signal peaks occurring within that interval were counted as a single puff, since these constituted a single functional inhalation. Multiple puffs were thus eliminated, preventing inflation of the puff count. Subsequently, analysis measured puff durations, peak flow, interpuff and intercigarette intervals, puff volumes were computed by integrating the area under the profile of each puff signal.

To analyze puffing behavior for evidence of compensatory smoking, it was decided to delete data from the first puff of each cigarette, since subjects were required to light the cigarettes, but not to smoke them.

*Procedure*

Each subject served in a repeated measures design—baseline, double and quadruple rates of smoking—reporting to the laboratory at the same time on three consecutive week days. The baseline (ad lib smoking) day was always first, the order of the two remaining conditions was randomized. Subjects were provided with cigarettes of their own brand, and permitted to smoke at their own rate during the baseline session. For the other conditions, subjects were told they were required to light each new cigarette upon instruction, but not to smoke unless they so chose. The number of cigarettes to be lit in each session was calculated as a multiple of the number smoked in the baseline session, and the lighting of cigarettes was spaced evenly across 120 minutes. For example, a subject smoking three cigarettes in baseline, was required to light a new cigarette every 20 minutes in the double rate session, and every 10 minutes in the quadruple rate session. Cigarettes were inserted into the plastic holder described above for monitoring and recording puffs. Television and reading matter were available during the two hour session, which took place in individual cubicles. Subjects were not required to abstain prior to sessions.

## RESULTS

*Topography*

Five parameters of puffing topography were measured and analyzed: number of puffs, puff duration, volume, peak flow (PKF), and interpuff interval (IPI). Table 2 summarizes this data in three ways: averaged across all subjects and all sessions (grand mean), averaged across all subjects for each session (session means), and baseline condition data for each subject. Puffing behavior is remarkably consistent across sessions, the largest variation occurring in number of puffs per session. Mean puff volume did not differ across conditions, $F(2,6)=0.19$, however, mean puff duration in condition B did differ significantly from the means in both condition 2B, $F(1,7)=7.23, p<0.03$, and 4B, $F(1,7)=9.96, p<0.02$.

Table 3 lists the intercorrelations based on data from all sessions between the main topographical variables: puff volume, duration and peak flow. Intrasubject correlations between puff volume and duration were generally high (mean=0.80), however, the intersubject correlation coefficient (using means for each subject) was only .17. This indi-

TABLE 2

PUFF TOPOGRAPHY MEAN AND STANDARD DEVIATION FOR PUFF PARAMETERS

| | No Puffs (Total) | Duration (sec) | Volume (cc) | PKF (cc/sec) | IPI (sec) |
|---|---|---|---|---|---|
| Baseline (B) | | | | | |
| 1 | 24 | 1 4 ± 0 8 | 50 1 ± 21 7 | 54 6 ± 6 2 | 54 4 ± 44 9 |
| 2 | 45 | 2 7 ± 1 0 | 46 3 ± 12 9 | 27 7 ± 6 6 | 47 4 ± 47 8 |
| 3 | 54 | 1 7 ± 0 5 | 31 1 ± 09 1 | 25 3 ± 3 8 | 31 9 ± 27 1 |
| 4 | 43 | 2 3 ± 0 7 | 48 3 ± 11 2 | 29 1 ± 6 8 | 36 4 ± 20 0 |
| 5 | 27 | 2 3 ± 0 4 | 71 5 ± 10 7 | 50 3 ± 11 5 | 82 4 ± 82 0 |
| 6 | 36 | 2 9 ± 0 9 | 69 0 ± 23 7 | 34 4 ± 8 5 | 42 0 ± 17 6 |
| 7 | 39 | 2 1 ± 0 5 | 114 9 ± 21 4 | 82 6 ± 14 5 | 48 5 ± 36 2 |
| 8 | 38 | 2 2 ± 0 6 | 93 4 ± 27 7 | 80 9 ± 36 3 | 34 1 ± 19 1 |
| Averaged Across Ss | | | | | |
| B | 38 2 | 2 2 ± 0 5 | 65 6 ± 27 6 | 48 1 ± 23 3 | 47 2 ± 16 2 |
| 2B | 46 4 | 1 8 ± 0 2 | 52 8 ± 18 2 | 45 3 ± 17 5 | 61 8 ± 24 3 |
| 4B | 64 2 | 1 8 ± 0 4 | 59 1 ± 24 6 | 49 5 ± 25 4 | 54 5 ± 29 7 |
| Averaged Across Ss and Sessions (Grand Mean) | | | | | |
| | 148 9 | 1 9 | 59 2 | 47 6 | 54 5 |

TABLE 3

CORRELATION COEFFICIENTS BETWEEN PUFF VOLUME DURATION AND PEAK FLOW

| | Correlation Coefficient (r) | | |
|---|---|---|---|
| Subject No | Volume × Duration | Volume × Peak Flow | Peak Flow × Duration |
| 1 | + 97 | + 09 | − 07 |
| 2 | + 71 | + 35 | − 27 |
| 3 | + 86 | + 75 | + 37 |
| 4 | + 87 | + 55 | + 14 |
| 5 | + 73 | − 19 | − 11 |
| 6 | + 89 | + 19 | − 20 |
| 7 | + 82 | + 41 | − 12 |
| 8 | + 54 | + 61 | − 25 |
| Mean | + 80 | + 34 | − 06 |

cates that although the relationships between puff volume and duration were very reliable for individuals, regression lines differed substantially across subjects

Volume was positively related to peak flow, though the range for individual subjects was much larger − 19 to + 75 The correlation based on subject means was quite high (r= 88) however, indicating that individuals who drew more forcefully from the cigarette were likely to take larger puffs The relationships between puff duration and peak flow were weak and variable (range of correlations − 25 to + 37)

These findings indicate that while measurement of puff duration or peak flow may provide a rough index of smoke volume taken into the mouth, substantial error may arise unless a within subjects design is employed and/or the relationship between volume and the other two parameters is established for each smoker

### *Analysis of Puffing Parameters for Evidence of Compensatory Smoking*

Three measures of smoking—cumulative volume, duration, and number of puffs—were compared across conditions (Fig 1) While compensation was substantial, total smoking increased from baseline to quadruple session conditions on each variable, reaching statistical significance for cumulative number of puffs, $F(2,14)=4\ 30$, $p<0\ 05$, $F(1,7)lin=5\ 73$, $p<0\ 05$, and cumulative puff volume, $F(2,14)=5\ 13$, $p<0\ 05$, $F(1,7)quad=7\ 57$, $p<0\ 05$

Per cigarette measures of cumulative number of puffs, volume, duration, and interpuff interval (IPI) were also compared across conditions (Table 4) Each of these variables showed significant decreases across conditions, as the number of cigarettes presented increased Both linear and quadratic trends were significant in each case Smoke intake was controlled primarily by changing the number of puffs and associated volume and duration taken per cigarette Individual puff volume did not change across conditions

A measure of smoke regulation, the "smoke titration index," is derived by comparing cumulative intake on a given variable in double and quadruple rate conditions to that in baseline This index is presented for cumulative number of puffs, volume and duration in Table 5 The following example illustrates how a ratio is calculated if a subject took a total of 50 puffs in baseline (B), 75 puffs in the 2B condition, and 100 puffs in the 4B condition, he would obtain a ratio of 0 75 for condition 2B, and 0 50 for condition 4B This is an example of undercompensation "Perfect" titration would be indicated by a ratio of 0 50 in the double rate condition and 0 25 in the quadruple rate condition, indicating that total intake had remained constant across conditions The mean

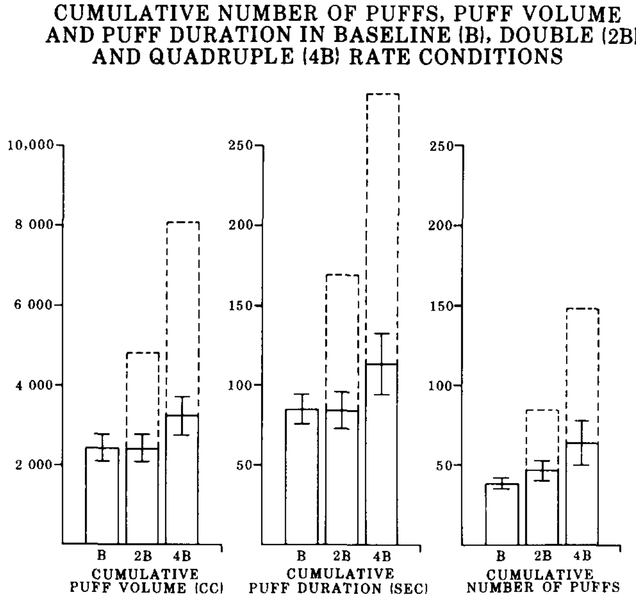


FIG 1 Cumulative volume duration and number of puffs in baseline (B), double (2B) and quadruple (4B) rate conditions Dashed lines indicate proportional increases in smoking that would have occurred in the absence of compensation Solid lines denote observed values (±standard error), demonstrating near perfect titration of smoke intake

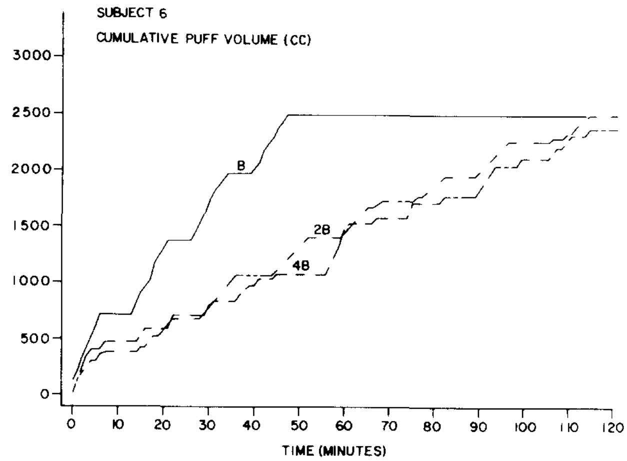


FIG 2 Cumulative puff volume over successive minutes in baseline (B), double (2B) and quadruple (4B) rate conditions for a subject displaying perfect compensation

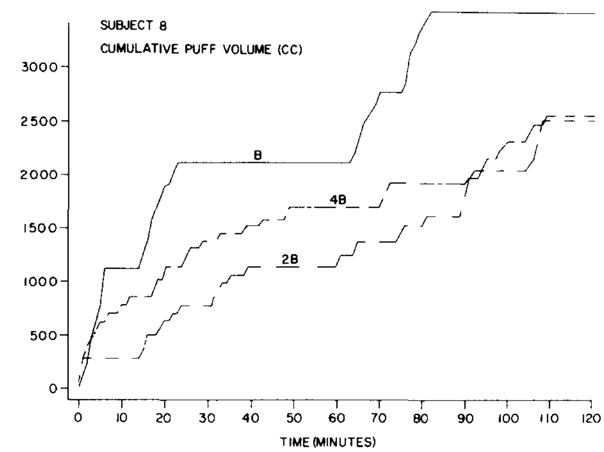


FIG 3 Cumulative puff volume over successive minutes in baseline (B), double (2B) and quadruple (4B) rate conditions for a subject displaying overcompensation

TABLE 4

PER CIGARETTE VALUES (MEAN ± s d ) OF SELECTED PUFF TOPOGRAPHY MEASURES NUMBER OF PUFFS, PUFF VOLUME DURATION, AND INTERPUFF INTERVAL (n=8)

| | Mean ± s d Session | | | | |
|---|---|---|---|---|---|
| Variable | B | 2B | 4B | F(2,14) | p< |
| Cumulative No | 9 3 | 5 8 | 4 1 | 36 88* | 0 0001 |
| Puffs/Cig | ±2 1 | ±2 2 | ±2 2 | | |
| Cumulative Puff | 600 0 | 292 5 | 205 5 | 26 25† | 0 001 |
| Vol/Cig (cc) | ±269 8 | ±136 4 | ±71 7 | | |
| Cumulative Puff | 20 4 | 10 4 | 7 2 | 50 86‡ | 0 0001 |
| Dur/Cig (sec) | ±4 8 | ±4 2 | ±3 0 | | |
| Cumulative | 418 1 | 311 5 | 184 5 | 23 16§ | 0 0001 |
| IPI/Cig (sec) | ±73 2 | ±51 1 | ±68 4 | | |

*F(1,7)lin=116 94, $p$<0 001, F(1,7)quad=7 71, $p$<0 03
†F(1,7)lin=23 64 $p$<0 002, F(1,7)quad=41 39, $p$<0 001
‡F(1,7)lin=57 33, $p$<0 001, F(1,7)quad=35 79, $p$<0 001
§F(1,7)lin=39 19, $p$<0 001

titration ratios for volume and duration correspond quite well for a given condition (0 48 vs 0 50 in the double rate condition and 0 35 vs 0 34 in the quadruple condition) Less agreement is found between mean ratios derived from number of puffs and volume or duration

On the other hand, an examination of titration ratios from individual subjects shows that measures computed from number of puffs, volume and duration are only modestly correlated The correlation between titration indices based on number of puffs and cumulative puff volume was 62 in the double rate condition and 43 in the quadruple condition ($p$>0 05) Similarly, titration indices based on volume and duration yielded correlations of 66 and 59 in the double and quadruple conditions, respectively ($p$>0 05) Ratios derived from duration and number of puffs were significantly related, however (r= 86 for both conditions, $p$<0 05) The linear increase in total duration with number of puffs reflects the relatively constant puff duration across subjects (cf Table 2) If puff volume is taken to represent the closest approximation to measuring smoke intake of the three measures, it is clear that just examining either of the other two measures may produce a misleading interpretation for a particular subject For puff volume, the "best titrators" in both conditions were S's 4 and 6, this degree of titration is not as evident

TABLE 5

SMOKE TITRATION INDEX CUMULATIVE NUMBER OF PUFFS, VOLUME AND DURATION BY SUBJECT

| Subject No | Number of Puffs $\frac{P_{2B}}{2P_B}$ | $\frac{P_{4B}}{4P_B}$ | Volume $\frac{V_{2B}}{2V_B}$ | $\frac{V_{4B}}{4V_B}$ | Duration $\frac{D_{2B}}{2D_B}$ | $\frac{D_{4B}}{4D_B}$ |
|---|---|---|---|---|---|---|
| 1 | 0 40 | 0 34 | 0 37 | 0 34 | 0 38 | 0 33 |
| 2 | 0 44 | 0 37 | 0 48 | 0 54 | 0 30 | 0 29 |
| 3 | 0 49 | 0 62 | 0 47 | 0 45 | 0 48 | 0 58 |
| 4 | 0 84 | 0 59 | 0 56 | 0 28 | 0 67 | 0 35 |
| 5 | 0 57 | 0 41 | 0 60 | 0 43 | 0 56 | 0 41 |
| 6 | 0 79 | 0 24 | 0 50 | 0 24 | 0 50 | 0 20 |
| 7 | 0 83 | 0 44 | 0 51 | 0 33 | 0 70 | 0 39 |
| 8 | 0 45 | 0 22 | 0 35 | 0 18 | 0 38 | 0 16 |
| Mean | 0 60 | 0 40 | 0 48 | 0 35 | 0 50 | 0 34 |
| s d | 0 19 | 0 15 | 0 09 | 0 12 | 0 14 | 0 13 |

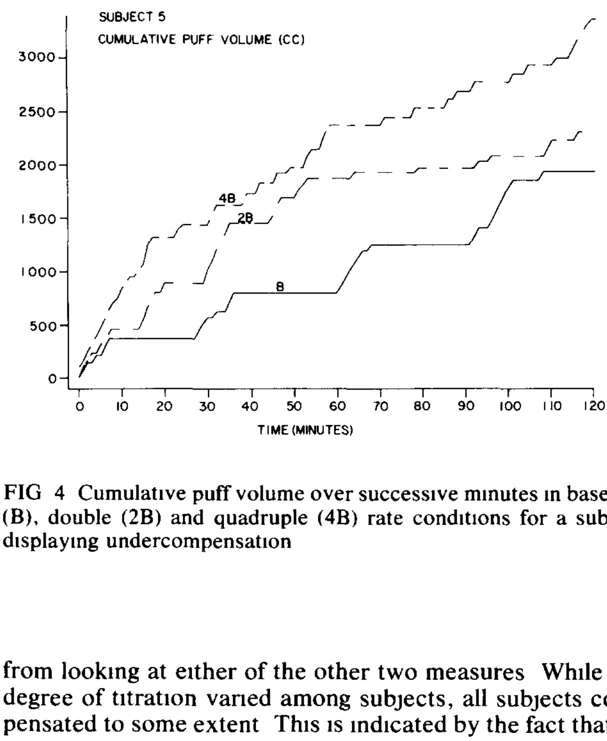


FIG 4 Cumulative puff volume over successive minutes in baseline (B), double (2B) and quadruple (4B) rate conditions for a subject displaying undercompensation

from looking at either of the other two measures While the degree of titration varied among subjects, all subjects compensated to some extent This is indicated by the fact that all titration indices are less than 1 0 in Table 5 Cumulative records exemplifying perfect compensation (no 6), overcompensation (no 8) and undercompensation (no 5) are displayed in Figs 2, 3 and 4

DISCUSSION

One of our main goals was to determine whether compensatory changes in smoking topography would occur in response to the increased rate of cigarette presentation Indeed, subjects titrated smoke intake remarkably well This is best summarized by the smoke compensation indices presented in Table 5 Compensation was virtually complete in the double rate condition, and substantial in the quadruple rate condition Breakdown in regulation at this extreme rate of cigarette presentation may reflect a number of factors, including stimulus control by lighting the cigarette and perceived demand characteristics It may have been difficult for some subjects to extinguish the cigarette almost immediately after lighting it, which would have been required for complete compensation in the quadruple rate conditions Variations in titration might also be due to unmeasured strategies of compensation, suvh as depth of inhalation

A second goal of the present study was to examine in detail the relationship between various measures of individual puff topography specifically puff volume, duration and peak flow As pointed out above, the relationships between these variables differed across subjects, although they were modestly correlated For a given subject, correlations were similar across conditions and were generally highest for volume × duration

While measures of cumulative number of puffs, volume and duration all reflect the compensation efforts of most subjects, discrepancies occurred between titration indices based on these various measures Marked differences between the titration index based on cumulative volume and those based on either duration and/or number of puffs, were observed in at least one condition for five of the eight subjects (2, 3, 4, 6 and 7) Identification of individual compensation behavior may thus be affected by which measure is employed We favor volume as the most accurate measure of tobacco product consumed, although the conclusions reached from an analysis of group means concur fairly well for all measures (Fig 1)

The terminology "compensators" and "noncompensators" has been employed to label presumably two classes of smokers, those who either respond or are insensitive to manipulations of cigarette characteristics to maintain constant smoke and/or nicotine intake Our results do not support the view of a bimodal distribution of smokers, since a continuous range of compensation ratios were obtained in the present study Compensators and noncompensators merely represent the extremes of this continuum

The present study examined downward titration, i e , reductions in smoking in response to an increased rate of cigarette presentation relative to baseline Downward titration has generally been found to be more complete than upward compensation in response to reduced cigarette lengths or nicotine yields [4, 7, 18, 19]

We did not specifically explore nicotine regulation per se in the present experiment, but rather, overall smoke intake Thus we cannot conclude with certainty whether the factors being regulated were nicotine, tar, oral stimulation, etc Although the direct comparison between nicotine vs tobacco smoke titration was not made in the present study, previous research suggests that smokers regulate smoke intake and number of puffs much more readily than nicotine intake [6,13]

It is likely, then, that the two factors—studying downward titration and tobacco smoke (as opposed to nicotine) regulation—accounted for the essentially perfect compensation observed in the double rate condition The combination of peripheral and central nervous system influences that may underly this precise regulation of tobacco smoke needs to be elucidated more fully One fruitful strategy may be to study the influence of nicotinic antagonists or manipulations of the sensory characteristics of smoke upon the robust titration observed in the present paradigm

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