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Original investigation

E-cigarette Dependence Measures in Dual Users: Reliability and Relations With Dependence Criteria and E-cigarette Cessation

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Abstract

Background: Electronic cigarettes (e-cigarettes) have drastically changed the nicotine and tobacco product landscape. However, their potential public health impact is still unclear. A reliable and valid measure of e-cigarette dependence would likely advance assessment and prognostication of the public health impact of e-cigarettes. The aim of this research was to examine the internal consistency, structure, and validity of three e-cigarette dependence scales.
Methods: Adult dual users (smokers who also vape, $N = 256$) enrolled in an observational cohort study (45.1% women, 70.7% white). At baseline, participants completed the e-cigarette Fagerström Test of Cigarette Dependence (e-FTCD), the e-cigarette Wisconsin Inventory of Smoking Dependence Motives (e-WISDM), and the Penn State Electronic Cigarette Dependence Index (PS-ECDI). All participants provided a urine sample for cotinine analysis and reported e-cigarette use at 1 year.
Results: The e-WISDM subscales had the highest internal consistency (α = .81–.96), then the PS-ECDI (α = .74) and e-FTCD (α = .51). A single-factor structure for the e-FTCD and an 11-factor structure for the e-WISDM were supported, but the PS-ECDI did not have a single-factor structure. All three e-cigarette dependence scales were highly correlated with validation criteria including continued e-cigarette use at 1 year, but not with e-liquid nicotine concentration or cotinine.
Conclusions: The e-WISDM and PS-ECDI had stronger internal consistency than did the e-FTCD, despite the e-FTCD's single-factor structure, but all 3 measures appear to be valid measures of e-cigarette dependence as suggested by their significant relations with self-perceived addiction, heavy use, early use after overnight deprivation, and continued use over time.
Implications: This research provides empirical support for three e-cigarette dependence measures: the e-FTCD, the PS-ECDI, and the e-WISDM among dual users of e-cigarettes and combustible cigarettes. The PS-ECDI and e-WISDM are more reliable, but all three measures were strongly correlated with key dependence constructs such as heavy use and continued use over time.

Introduction

Electronic cigarettes (e-cigarettes) provide nicotine in a vapor rather than through combustion. Since they were introduced in 2003, e-cigarette use has increased dramatically.[1,2] In 2014, it was estimated that 3.7% of adults in the United States currently used e-cigarettes[3,4] and by 2016 it was estimated that 4.5% of adults used e-cigarettes, translating to 10.8 million current adult e-cigarette users in the United States.[5] However, data from 2017 indicate that only 2.8% of adults use e-cigarettes every day or some days.[6] The popularity of this product and the evidence that e-cigarettes are lower risk than combustible cigarettes,[4] suggest that e-cigarettes could improve public health. However, key knowledge gaps remain concerning e-cigarettes. For instance, there is a need for more evidence on their addiction potential and how to measure it (ie, how to measure e-cigarette dependence).

Glasser et al.[7] conducted a systematic review of the published research on the effects of e-cigarettes. The authors found dozens of studies related to the nicotine concentration, pharmacokinetics, the subjective effects of vaping, and e-cigarettes' ability to alleviate smoking withdrawal symptoms. However, they identified only one published measure of e-cigarette dependence, the Penn State Electronic Cigarette Dependence Index (PS-ECDI[8]). Multiple authors have identified this gap in e-cigarette research, noting that reliable and valid measures of e-cigarette dependence are needed to inform the appraisal of the potential public health impacts of e-cigarettes.[9–12]

The current article examines the internal consistency, structure, and validity of three distinct e-cigarette dependence measures. The first measure is the 10-item PS-ECDI (see Supplementary Appendix 1). The PS-ECDI was explicitly developed in tandem with the Penn State Cigarette Dependence Index (PS-CDI), using constructs derived from other dependence measures (eg, the Hooked on Nicotine Checklist (HONC[12]), the Fagerström Test of Cigarette Dependence (FTCD[13,14]). In a sample of former smokers who used e-cigarettes, the PS-CDI and PS-ECDI scores were meaningfully correlated ($r = .35, p < .01$) and respondents tended to report lower dependence scores with regard to their current e-cigarette use versus their prior cigarette use. PS-ECDI scores were positively related to higher nicotine concentration of e-liquid. Although internal consistency was not presented in this article, a subsequent study of online e-cigarette users reported moderate internal consistency for the PS-CDI ($\alpha = .72$) and PS-ECDI ($\alpha = .71$).[15] No published data have examined the structure of these measures, but it is computed as a single score, therefore, it appears to have been designed to be a unidimensional measure.

The second measure is an adaptation of the FTCD[13,14] (see Supplementary Appendix 1). The e-cigarette FTCD or e-FTCD is a 6-item measure adapted from the FTCD by changing all references to cigarettes to e-cigarettes and all references to smoking to vaping. Browne and Todd[16] created the FTND-V, a similar measure but included additional items that addressed e-cigarette usage (eg, e-liquid quantity and concentration, resistance coil, wattage). The FTND-V did not have strong internal consistency ($\alpha = .54$) among former smokers who were using e-cigarettes, but it was related to e-liquid nicotine concentrations.[16] The FTCD was developed as a single-factor measure of physical dependence, although studies have shown evidence contradicting this factor structure.[17–19] No factor analyses have been conducted on the e-cigarette Fagerström Test of Cigarette Dependence (e-FTCD).

The third measure is a 34-item adaptation (P. Hendricks, personal communication, June 10, 2015) of the Brief Wisconsin Inventory of Smoking Dependence Motives (WISDM[20,21]; see Supplementary Appendix 1), the e-WISDM. The e-cigarette Wisconsin Inventory of Smoking Dependence Motives (e-WISDM) includes 11 subscales and two overarching subscales: Primary Dependence Motives (PDM) and Secondary Dependence Motives (SDM).[22] The e-WISDM subscales address many of the key constructs suggested by the Tobacco Center for Regulatory Science Measurement Workgroup[9]: for example, craving and/or urges to use in the Craving subscale, sensory dependence in the Taste/Sensory Properties subscale, perceived benefits in the Cognitive Enhancement and Affect Regulation subscales, automaticity in the Automaticity subscale, and tolerance in the Tolerance subscale, but not all (ie, the e-WISDM does not gather point estimates of e-cigarette quantity and frequency of use, nor does it address use despite harms, or preference for e-cigarettes over competing rewards). To date, no data have been published on the internal consistency or factor structure of the e-WISDM.

In addition to examining the internal consistency and structure of the three e-cigarette dependence measures (PS-ECDI, e-FTCD, and e-WISDM), this research examined the validity of the three measures. We examined the correlation among these measures given that they ostensibly target the same construct. We evaluated the construct validity of the e-cigarette measures by determining their relations with important construct indicators[23] comprised by the dependence nomological network: for example, heaviness of use, morning use latency, and self-perception of "addiction."[12,23–27] First, we related dependence scores with use indices; that is, for e-cigarettes, vape events/day (a vape event was defined as about 15 puffs or lasting about 10 minutes), vapes per puff event, and nicotine concentration in users' e-liquid. Second, we examined biomarkers of heaviness of use. Specifically, we examined urine cotinine and the molar sum of urine cotinine and 3-hydroxycotinine (3HC)[28] to efficiently examine daily nicotine intake independent of individual metabolic differences. Third, we examined cigarette smoke exposure via 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol and its glucuronides (total NNAL). Finally, given that high dependence should predict longer-term use of e-cigarettes, we examined the ability of the three measures to predict participants' use of e-cigarettes 1 year after the baseline assessments. In addition to providing insight into the validity of these three measures, these validation analyses provide important data to inform our understanding of the construct of e-cigarette dependence.

Methods

Participants were recruited for this longitudinal observational trial via television and social media (eg, Facebook) advertisements in the greater Madison and Milwaukee, Wisconsin, areas from October 2015 to July 2017. Interested people were phone screened for eligibility: at least 18 years old, able to read and write English, have *no* plans to quit smoking and/or e-cigarette use in the next 30 days, not currently using smoking cessation medication, and not currently in treatment for psychosis or bipolar disorder. Participants also had to be either exclusive smokers (ie, smoked at least 5 cigarettes/day for the past 6 months and not used e-cigarettes within the last 6 months) or dual users (used nicotine-containing e-cigarettes at least once a week for the past month and have smoked daily for the last 3 months). We had initially set a minimum of 5 cigarettes/day for dual users but in order to increase recruitment, approximately 6 months into our 2-year recruitment we loosened the cigarettes/day criteria for dual users so that they just needed to have smoked daily for the last 3 months. We will include only dual users in this analysis.

Eligible participants provided informed written consent and completed baseline assessments of demographics, smoking and e-cigarette history, cigarette and e-cigarette use patterns, and beliefs about cigarettes and e-cigarettes including rating the importance of different reasons for using e-cigarettes using a 3-point scale from 1 = Not at all important to 3 = Extremely important. All participants completed the FTCD,[14] the Brief WISDM,[20,21] and the PS-CDI.[8] Dual users also completed three parallel e-cigarette dependence measures:

the e-FTCD, the e-WISDM (P. Hendricks, personal communication), and the PS-ECDI.[8]

At baseline, all participants provided a breath sample for carbon monoxide determination and a urine sample for baseline cotinine, 3HC, and NNAL analysis. Urine cotinine, 3HC, and total NNAL were measured by liquid chromatography–mass spectrometry in the Clinical Pharmacology Laboratory at the University of California San Francisco.[29,30] Participants attended a 1-year follow-up visit where they completed measures of cigarette and e-cigarette use patterns.

Analytic Plan

Means, SDs, and Cronbach's α's were computed for all dependence scales and subscales. Single-factor confirmatory factor analyses (CFAs) were conducted for the e-FTCD and PS-ECDI and 11-factor and 2-factor CFAs were conducted for the e-WISDM using Mplus.[31] For the PS-ECDI and e-FTCD, items were modeled as categorical indicators (binary and ordered categorical variables) using the robust weighted least squares means and variance-adjusted (WLSMV) estimator recommended for categorical variables.[31] The e-WISDM items were modeled as continuous indicators using a maximum likelihood estimator. Good fit was evidenced by comparative fit index (CFI; ≥.90), Tucker–Lewis index (TLI; ≥.95), root mean squared error of approximation (RMSEA; <.08), and standardized root mean square residual (SRMR; <.08). Bivariate correlations were used to examine relations among the scales and subscales including the e-WISDM PDM that assess heavy, automatic vaping, and e- SDM that assess instrumental dependence motives.[22] To examine construct validity for e-cigarette dependence measures we computed correlations with self-reported addiction on a 0–100 point scale, vapes/day, vaping days/week, time to first vape, nicotine concentration of e-liquid, cotinine, the molar sum of cotinine and 3HC (cotinine + 3HC), and total NNAL. We examined the predictive validity of the dependence scales to predict smoking status and e-cigarette use at year 1 using logistic regression. Finally, to further explore the nomological network of e-cigarette dependence, we examined the relations between the e-cigarette measures and reported reasons for use of e-cigarettes using bivariate correlations.

Table 1. Dual User Demographics (*N* = 256)

Gender, *N* (%)	
Women	115 (45.1)
Men	140 (54.9)
Race, *N* (%)	
White	181 (70.7)
African American	34 (13.3)
Multiracial	23 (9.0)
Hispanic, *N* (%)	17 (6.6)
Education, *N* (%)	
More than high school	167 (65.7)
High school/GED	70 (27.6)
Less than high school	17 (6.7)
Psychiatric history, *N* (%)	156 (61.2)
Age, mean (SD)	39.0 (13.8)
Cigarettes/d, mean (SD)	12.5 (7.4)
Vaping d/wk, mean (SD)	5.5 (1.9)

Results

Participants (*N* = 256) had a mean age of 39.0 years old (SD = 13.8) and slightly more than half were men (54.9%). See Table 1 for demographics. The majority of participants (65.3%) used refillable tank systems and almost all used e-liquid-containing nicotine. Only six participants reported use of 0 mg nicotine e-liquid concentration; almost half of the sample (47%) used e-liquid with a nicotine concentration of at least 7–12 mg.

Internal Consistency and Structure

Internal consistency was relatively low for the e-FTCD (α = .51) but adequate for the PS-ECDI (α = .74). The e-WISDM Total and subscales all exceeded the α = .80 threshold as recommended by Nunnally and Bernstein[32] (see Table 2). The CFA for a single-factor e-FTCD showed good fit (CFI = .99, TLI = .99, RMSEA = .02, SRMR = .08) but the CFA results did not support a single-factor structure for the PS-ECDI (CFI = .91, TLI = .89, RMSEA = .12, SRMR = .14). The 11-factor CFA for the e-WISDM (CFI = .91, TLI = .89, RMSEA = .076, SRMR = .05) appeared to be a better fit than the 2-factor model (CFI = .91, TLI = .89, RMSEA = .12, SRMR = .05).

Table 2. Descriptive Statistics and Internal Consistency of Combustible and E-cigarette Dependence Measures

	No. of items	Mean (SD)	Cronbach's α
e-FTCD	6	2.65 (2.10)	.51
PS-ECDI	9	6.57 (4.72)	.74
e-WISDM Total	37	31.81 (13.38)	.96
e-WISDM PDM	16	2.72 (1.49)	.96
e-WISDM SDM	21	2.99 (1.16)	.93
e-WISDM Affiliative Attachment	3	1.90 (1.36)	.91
e-WISDM Affective Enhancement	3	3.27 (1.78)	.88
e-WISDM Automaticity	4	3.08 (1.91)	.94
e-WISDM Loss of Control	4	2.12 (1.37)	.90
e-WISDM Cognitive Enhancement	3	3.11 (1.94)	.94
e-WISDM Craving	4	3.07 (1.65)	.87
e-WISDM Cue Exposure	3	2.87 (1.64)	.81
e-WISDM Social/Environmental Goads	3	2.56 (1.70)	.92
e-WISDM Taste	3	5.36 (1.67)	.92
e-WISDM Tolerance	4	2.59 (1.76)	.89
e-WISDM Weight Control	3	1.88 (1.43)	.89

e-FTCD = e-cigarette Fagerström Test of Cigarette Dependence; e-WISDM = e-cigarette Wisconsin Inventory of Smoking Dependence Motives; PS-ECDI = Penn State Electronic Cigarette Dependence Index.

Dependence Scale Intercorrelations

The e-cigarette measures demonstrated strong intercorrelations. The PS-ECDI was most strongly correlated with the e-FTCD (r = .87) and the e-WISDM PDM (r = .81; see Table 3). The e-WISDM PDM subscale was more strongly related to the e-FTCD and PS-ECDI than was the e-WISDM SDM subscale (.73–.81 vs. 53–.64, respectively).

Validity

The validity of the e-cigarette dependence scales was further evaluated via their relations with self-report measures (self-rating of addiction to e-cigarettes, vapes/day, vaping days/week, time to first vape, nicotine concentration typically used) and with the three biomarkers (cotinine, cotinine + 3HC, and NNAL). The e-FTCD, PS-ECDI, e-WISDM Total, and various e-WISDM subscales (including PDM and SDM) were significantly related to self-reported addiction to e-cigarettes. Self-rated addiction was not strongly related to self-reported vapes/day. Vaping days/week was especially highly related to the e-FTCD and the e-WISDM Tolerance subscale (see Table 3). Biomarkers of nicotine intake were inconsistently and very modestly related to all the e-cigarette dependence measures including number of self-reported vapes/day. However, NNAL was significantly and negatively related to the PS-ECDI, e-FTCD, and various e-WISDM measures (Total score, PDM, Tolerance, Loss of Control, Taste, and Automaticity). The relations between the e-cigarette dependence measures and the self-report and biochemical criteria were affected very little by partialling self-reported cigarettes/day from the relations.

With respect to future behavior, we found that 93 of the 205 dual users (45.4%) who completed the 1-year follow-up reported no e-cigarette use in the previous 30 days. Self-reported 30-day point-prevalence abstinence from e-cigarettes among dual users was significantly predicted by lower scores on the: e-FTCD (OR = .76, p < .01), PS-ECDI (OR = .85, p < .01), e-WISDM Total (OR = .96, p = .01), e-WISDM PDM (OR = .62, p = .002), and e-WISDM SDM (OR = .70, p = .03) as well as lower scores on the e-WISDM Affiliative Attachment (OR = .73, p = .04), e-WISDM Automaticity (OR =.73, p=.003), e-WISDM Loss of Control (OR = .66, p = .01), e-WISDM Craving (OR = .67, p = .002), e-WISDM Taste/Sensory Properties (OR = .80, p = .04), and e-WISDM Tolerance (OR = .70, p = .01) subscales. Lower frequency e-cigarette use (vaping days/week) also predicted abstinence (OR = .94, p = .03).

Participants were asked why they used their e-cigarettes (eg, they might be less harmful to me than cigarettes, I like the flavors, to help with nicotine withdrawal when I can't smoke, they are cheaper than smoking, to avoid having to go outside, to cut down on my smoking, to completely quit smoking cigarettes). The e-FTCD, e-WISDM, e-WISDM PDM, e-WISDM SDM, and PS-ECDI were positively related to the importance of a variety of reasons for using e-cigarettes (see Table 4), although the e-FTCD had the fewest significant relations with reasons for vaping. The strongest relations across all of the dependence measures were vaping when you cannot smoke, liking the flavor, and enjoying socializing with e-cigarettes.

Discussion

This research evaluated e-cigarette dependence measures in 256 dual users of cigarettes and e-cigarettes who were followed for 1 year. The three e-cigarette dependence measures evaluated in this research were based upon existing measures of combustible cigarette dependence. The e-cigarette dependence measures (e-FTCD, PS-ECDI, and e-WISDM) were found to differ in reliability and latent factor structure, but in general, showed meaningful relations with e-cigarette

Table 3. Correlations With E-cigarette Dependence Measures With E-cigarette Self-report and Biomarker Dependence Criteria Among Dual Users

	Self-rated addiction	Vapes/d	Vaping d/wk	Time to first vape	Nicotine concentration	Cotinine	Molar sum of cotinine and 3HC	NNAL
Vapes/d[a]	.18*	—	.30**	.31**	−.12	−.05	−.03	−.13
Vaping d/wk	.33**	.30**	—	.33**	−.26**	−.02	−.01	−.15
e-FTCD	.56**	.48**	.43**	.85**	.02	−.09	−.05	−.20**
PS-ECDI	.71**	.39**	.43**	.79**	.02	−.03	−.002	−.16*
e-WISDM Total	.69**	.23**	.31**	.55**	.02	−.14	−.13	−.18*
e-WISDM PDM	.72**	.30**	.39**	.61**	.03	−.14	−.13	−.20*
e-WISDM SDM	.61**	.16*	.22**	.46**	.02	−.12	−.12	−.15*
e-WISDM Affiliative Attachment	.46**	.06	.09	.34**	.07	−.11	−.13	−.08
e-WISDM Affective Enhancement	.54**	.07	.18*	.42**	.12	−.08	−.08	−.10
e-WISDM Automaticity	.54**	.33**	.36**	.49**	.03	−.16*	−.12	−.18*
e-WISDM Loss of Control	.71**	.18*	.25**	.49**	.07	−.17*	−.19*	−.16*
e-WISDM Cognitive Enhancement	.52**	.17*	.20**	.37**	.04	−.09	−.10	−.15*
e-WISDM Craving	.72**	.15*	.33**	.50**	.04	−.09	−.07	−.06
e-WISDM Cue Exposure	.57**	.11	.18*	.40**	.03	−.16*	−.08	−.07
e-WISDM Social/Environmental Goads	.19**	.16*	.10	.25**	−.08	−.08	−.05	−.09
e-WISDM Taste	.30**	.13	.21**	.21**	−.11	−.08	−.10	−.18*
e-WISDM Tolerance	.62**	.36**	.43**	.67**	−.02	−.09	−.10	−.28**
e-WISDM Weight Control	.42**	.05	.13	.29**	.01	−.04	−.03	−.10

e-FTCD = e-cigarette Fagerström Test of Cigarette Dependence; e-WISDM = e-cigarette Wisconsin Inventory of Smoking Dependence Motives; PDM = Primary Dependence Motives; PS-ECDI = Penn State Electronic Cigarette Dependence Index; SDM = Secondary Dependence Motives.

[a]On days when you vape, how many times per day do you usually use your electronic cigarette? (Assume one "time" consists of around 15 puffs, or lasts around 10 minutes.)

*p < .05, **p < .01.

Table 4. Correlations Among Measures Among Measures of E-cigarette Dependence and Reasons for E-cigarette Use

	e-FTCD	PS-ECDI	e-WISDM Total	e-WISDM PDM	e-WISDM SDM
Dependence measures					
e-FTCD					
PS-ECDI	.87**				
e-WISDM Total	.65**	.75**			
e-WISDM PDM	.73**	.81**	.93**		
e-WISDM SDM	.53**	.64**	.96**	.80**	
Reasons for e-cigarette use					
Use e-cigarettes when I can't smoke	.24**	.24**	.21**	.22**	.18*
Might be less harmful	.13	.22**	.23**	.21**	.22**
I like the flavors	.15*	.19*	.24**	.17*	.27**
May help me quit smoking	.13	.24**	.17*	.18*	.15*
E-cigarettes don't smell	.03	.09	.24**	.20**	.24**
I like socializing with e-cigarettes	.20**	.24**	.37**	.29**	.39**
I prefer the taste	.27**	.29**	.34**	30**	.33**
Less toxic	.09	.12	.18*	.14	.19**
Help with nicotine withdrawal	.01	.12	.19**	.17*	.19*
To avoid having to go outside to smoke	.02	.03	.16*	.10	.19*
To cut down on cigarette smoking	.14	.21**	.22**	.22**	.20**
To completely quit smoking	.14	.20**	.22**	.23**	.20**

Reasons were only included in the table if they were statistically significantly correlated with at least one dependence measure. e-FTCD = e-cigarette Fagerström Test of Cigarette Dependence; e-WISDM = e-cigarette Wisconsin Inventory of Smoking Dependence Motives; PDM = Primary Dependence Motives; PS-ECDI = Penn State Electronic Cigarette Dependence Index; SDM = Secondary Dependence Motives.
$^{*}p < .05$; $^{**}p < .01$.

dependence criteria; they tended to be strongly intercorrelated, and were correlated with key measures of dependence such as self-rated addiction, self-report of vaping heaviness, and likelihood of continuing to use e-cigarettes over the subsequent year.

Understanding the structure of these three measures is important in understanding how they function. Although the e-FTCD may have poor internal consistency, the CFA results clearly supported a single-factor structure. This may be due to the fact that the six items all had small loadings on the latent factor and coefficient α is sensitive to small factor loadings. In addition, the relatively low coefficient α may reflect the fact that these items are tapping the breadth of a large multifaceted construct and therefore are less related to each other than items that focus on a more discrete construct element (eg, tolerance). Conversely, although the PS-ECDI has fair internal consistency, it is clearly not a single-factor measure. At present, its optimal structure and related substantive interpretation are unknown. The CFAs for the e-WISDM support an 11-factor structure, consistent with the WISDM. However, a 2-factor structure did have some evidence of support as well, consistent with its empirically derived conceptualization[22] as reflecting two higher order factors (the PDM and SDM). Future research will reveal whether the conceptualization of dependence and the utility of e-cigarette dependence measures are better served by single or multifactorial approaches. In the case of combustible cigarette dependence, multiple factors seem to provide complementary information.[22,33–37]

There was substantial evidence that all three e-cigarette dependence measures had significant and meaningful relations with important indices or putative correlates of e-cigarette dependence, providing insight into the e-cigarette dependence nomological network. For instance, the PS-ECDI and the e-WISDM PDM subscales were especially highly related to self-perceptions of addiction to e-cigarettes. Perceived loss of control or addictiveness may be a useful e-cigarette dependence criterion as it may reflect the cumulative influence of multiple dependence mechanisms or processes and may be relatively unaffected by contextual or lifestyle constraints on product use (eg, inability to use at work). Further, there is evidence that self-perceived addiction or perceived loss of control is meaningfully related to other dependence measures and criteria.[12,22,24] Moreover, this criterion has public health relevance as a large percentage of dual users do not believe that e-cigarettes are addictive.[26]

The e-FTCD and PS-ECDI and the e-WISDM PDM subscales such as Tolerance had fairly strong and consistent relations with self-reported vaping heaviness (vaping days/week). However, the lack of strong relations of vaping days/week with biomarkers of use raises questions about (1) whether differences in biomarkers could be masked in the dual users by their cigarette smoking, (2) how accurately e-cigarette users can report on self-administration,[38] and (3) whether such a crude index of self-administration is in fact, fundamentally poorly related to actual drug delivery and dependence.

Time to first cigarette is a valid measure of smoking dependence.[33] Therefore, it is important to determine if latency to vape is similarly valid with regard to e-cigarette dependence. The e-FTCD and the PS-ECDI both ask about time to first vape and both were quite strongly related to the self-report of this specific measure, likely due, somewhat, to criterion contamination. However, this latency measure was fairly highly correlated with all measures of dependence, including all e-WISDM subscales, suggesting that time to first vape is an important dependence indicator.

Interestingly, self-reported addiction, e-cigarette dependence measures, and biomarkers of use were all unrelated to self-reported e-liquid nicotine concentration. Foulds et al.[8] found a positive relation of PS-ECDI scores and e-liquid nicotine concentration; however, even those using e-liquid with no nicotine endorsed markers of dependence in that study. The findings from this study suggest that, at least among dual users, dependence is not consistently related to e-liquid nicotine concentration, consistent with titration studies that have found nicotine exposure is also related to use features (eg, longer puffs) and device features (eg, higher voltage batteries),[39] and with the recommendations of Pearson et al.[40] to simply assess presence of nicotine versus nicotine concentration.

E-cigarette dependence was not significantly related to general exposure to nicotine, which is the opposite of what the nomological network would predict. This may be due to the difficulty discerning the source of nicotine in the cotinine and cotinine + 3HC assays (ie, the nicotine could be from combustible or e-cigarettes). However, there was a fairly consistent and potentially important relation between some of the dependence measures and total NNAL level, a biomarker of exposure to combustible tobacco. For instance, the e-WISDM Tolerance subscale was negatively related to NNAL (r = −.28). Thus, it appears that to the extent that dual users were dependent on e-cigarettes, they were less likely to smoke combustible cigarettes in a manner that delivered high levels of this carcinogen. It is interesting to note that among dual users, measures of cigarette dependence such as the FTCD, PS-CDI, and WISDM Tolerance were positively and significantly related to NNAL (data not shown). This suggests that while dependence on cigarettes drives greater smoking intensity and therefore greater exposure to carcinogens such as NNAL (see Table 3), dependence on e-cigarettes may result in decreased smoking intensity and therefore decreased toxicant exposure. This is consistent with the notion that harm reduction from dual use is especially likely if the modified risk tobacco product can produce a level of dependence that supplants dependence on cigarettes.[41] Of course, the negative association between e-cigarette dependence and NNAL might be fortuitous or dual users might have independently decided to smoke less intensely and their greater dependence on e-cigarettes could merely be a consequence of that choice. There are other important caveats that must be considered regarding the relation of NNAL with e-cigarette dependence. First, we do not know if this relation would apply to other combustion-related toxicants. Second, we do not know if a reduction in exposure of this magnitude would have significant health effects.[42] Finally, any such benefit would no doubt be reduced to the extent that dual use leads to a longer duration of smoking combustible cigarettes.

Prediction of likelihood of cessation is often considered a dependence criterion.[37,43] Therefore, the association of e-cigarette dependence measures with the likelihood of discontinuation of e-cigarette use at 1-year follow-up provides an important additional index of construct validity of the e-cigarette dependence measures. The association between e-cigarette dependence and e-cigarette cessation may also have public health value as it might allow an accurate estimate the prevalence of intransigent e-cigarette use and permit identification of those who are most likely to be intransigent. The e-FTCD, e-PS-ECDI, and multiple e-WISDM measures predicted the likelihood of discontinuation of e-cigarette use. The particular WISDM subscales that were especially efficient predictors of cessation likelihood comprise both PDM and SDM, suggesting that both play a role in sustaining e-cigarette use. Thus, persistent e-cigarette use was related to factors such as taste and sensory enjoyment, and use that was heavy, automatic and accompanied by strong craving. These findings suggest the value of a multifactorial approach to dependence assessment and provide additional insight into the factors that may motivate continued e-cigarette use.

Finally, this research suggests that like cigarette dependence,[22,44] heavy and persistent use of e-cigarettes is especially highly related to PDM. E-cigarettes have been characterized as providing less nicotine than combustible cigarettes[45–48] although this may be changing as e-cigarettes become more efficient nicotine delivery devices.[49] Further, evidence suggests that sensory features such as flavors might significantly motivate their use,[50–54] and in this sample liking the flavor was significantly positively related to all of the dependence measures. This suggests that the use of e-cigarettes might be more highly related to SDM than is the case for cigarettes (eg, motives such as using for taste or for social reasons). Instead, the available data show that dependence motives associated with heavy and ongoing use of e-cigarettes are the same as those most highly associated with cigarette use (eg, high levels of craving and automatic use patterns accompanied by a subjective sense of loss of control). The structure of the two types of dependence and their interrelations should be formally explored in further research.

This research has limitations and clearly highlights the need for additional investigation. First, the e-cigarette dependence measures were examined only among dual users of e-cigarettes and combustible cigarettes. Future research is needed to validate these measures among people who only vape to ensure that these measures perform consistently across both groups. One study did find that exclusive vapers had a shorter latency to first vape than dual users and were more likely to use second- or third-generation e-cigarettes and lower nicotine concentration e-liquid.[55] Second, this study showed that a 1-factor model did not provide adequate fit with regard to the PS-ECDI. Future research is needed to establish the factor structure and improve the psychometrics of this measure. Third, this study did not evaluate the 22-items from the Patient Reported Outcomes Measurement Information System (PROMIS) Nicotine Dependence Item Bank[56–58] as it was not available when this study was launched. This scale was identified by the Tobacco Center for Regulatory Science (TCORS) Measurement Workgroup as promising in that it assesses e-cigarette dependence constructs identified by this group, with the exception of tolerance, perceived benefits, and sensory dependence.[9] A recent study found that a 4-item e-cigarette version was related to vaping frequency.[59] Fourth, recruitment began in 2016, just as pod mod e-cigarettes and nicotine salt e-liquid were entering the market. Therefore, these data do not address dependence on these products. Finally, future research is needed to understand how e-cigarette and combustible cigarette measures are related to one another in dual users.

Despite these limitations, the results of this study are clear. Among dual users, although the PS-ECDI and e-WISDM are more reliable measures of e-cigarette dependence, and the e-WISDM and e-FTCD have adequate to good structural fit, all three scales (the e-FTCD, PS-ECDI, and e-WISDM) appear to be valid measures of a construct that leads to self-perceived addiction, heavy use, early use after overnight deprivation, and continued use over time.

Supplementary Material

Supplementary data are available at *Nicotine and Tobacco Research* online.

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Declaration of Interests

None declared.

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