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REVIEW

ADDICTION SSA

Concurrent validity of the marijuana purchase task: a meta-analysis of trait-level cannabis demand and cannabis involvement

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Abstract

Background and aims: The Marijuana Purchase Task (MPT) is increasingly used to measure cannabis reinforcing value and has potential use for cannabis etiological and regulatory research. This meta-analysis sought to evaluate for the first time the MPT's concurrent validity in relation to cannabis involvement.

Methods: Electronic databases and pre-print repositories were searched for MPT studies that examined the cross-sectional relationship between frequency and quantity of cannabis use, problems, dependence, and five MPT indicators: intensity (i.e. unrestricted consumption), O_{max} (i.e. maximum consumption), P_{max} (i.e. price at which demand becomes elastic), breakpoint (i.e. first price at which consumption ceases), and elasticity (i.e. sensitivity to rising costs). Random effects meta-analyses of cross-sectional effect sizes were conducted, with *Q* tests for examining differences by cannabis variables, meta-regression to test quantitative moderators, and publication bias assessment. Moderators included sex, number of MPT prices, variable transformations, and year of publication. Populations included community and clinical samples.

Results: The searches yielded 14 studies (n = 4077, median % females: 44.8%: weighted average age = 29.08 [SD = 6.82]), published between 2015 and 2022. Intensity, O_{max}, and elasticity showed the most robust concurrent validity ($|r$'s$|$ = 0.147–325, *ps* < 0.014) with the largest significant effect sizes for quantity ($|r|$ intensity = 0.325) and cannabis dependence ($|r|$ O_{max} = 0.320, $|r|$ intensity = 0.305, $|r|$ elasticity = 0.303). Higher proportion of males was associated with increased estimates for elasticity-quantity and P_{max}-problems. Higher number of MPT prices significantly altered magnitude of effects sizes for P_{max} and problems, suggesting biased estimations if excessively low prices are considered. Methodological quality was generally good, and minimal evidence of publication bias was observed.

Conclusions: The marijuana purchase task presents adequate concurrent validity to measure cannabis demand, most robustly for intensity, O_{max}, and elasticity. Moderating effects by sex suggest potentially meaningful sex differences in the reinforcing value of cannabis.

KEYWORDS
Behavioral economics, cannabis, demand, marijuana purchase task, meta-analysis, validity

INTRODUCTION

Cannabis is one of the most widely used drugs in North America and European countries, and its past year prevalence is estimated in the range of 7.1%–9.5% [1, 2]. In the last decade, past-month prevalence of cannabis use increased by 27% in European adults, with most pronounced relative increases observed in adults ages 35 to 64 [3]. In the United States, more frequent use occurs at younger ages (18–34) [4], and rates are higher (11.3%–25%) among states that have legalized its use for recreational purposes [5], although whether that is an antecedent or consequence of legalization remains unclear.

The combination of rising prevalence rates, risky patterns of use, tetrahydrocannabinol (THC) levels, and cannabis risks/harms raises the need to understand the determinants of cannabis use [3, 6, 7]. Cannabis demand, a measure of the relative reinforcing value of the drug, has received increasing attention in the last few years [8–11] and is typically assessed using hypothetical purchase tasks (HPTs) [12]. A plethora of HPTs have been developed for different drugs, and meta-analyses have provided evidence on their validity to assess legal (e.g. tobacco and alcohol) [13–17] and illicit substances demand [18]. The marijuana purchase task (MPT) quantifies units (e.g. hits/puffs, grams, and joints) that an individual estimates wanting to purchase for consumption at increasing prices, typically over either a 24-h period or a week (i.e. trait demand), but in some designs in the moment (i.e. right now) [12], with the latter referred to state demand. The MPT offers five demand indicators that capture different aspects of cannabis reinforcing value and correlate with different aspects of cannabis use (frequency and quantity of use), consequences, and hazardous patterns of drug use (e.g. heavy use and cannabis use disorder [CUD]) [19–21]. These map to the overall topography of the canonical behavioral economic curve and comprise intensity (consumption at zero or minimal cost, the Y-axis intercept), elasticity (the proportionate slope of the decelerating curve as a function of increases in price), O_{max} (i.e. maximum expenditure over the course of the demand curve), P_{max} (i.e. the price at which demand becomes elastic), and finally breakpoint (i.e. the first price at which consumption is zero, the termination of the demand curve) [12].

Cannabis reinforcing value has clinical relevance to cannabis misuse because it allows measuring individual differences in cannabis reinforcing value that may have use in identifying individuals who are at risk for CUD [21] and may benefit from interventions [22]. MPT indicators may also be useful for informing cannabis pricing policies in legal jurisdictions [23]. In this context, there is large interest in applying substitution paradigms [8], to inform the extent to which consumption of a particular drug will change based on availability of another drug (i.e. illegal vs legal cannabis). The policy measures to regulate the cannabis market significantly differ with respect to access, labeling, marketing, and pricing/taxation [24, 25], and evaluating the impact of these measures on cannabis consumption (demand) can inform the estimated public health impact.

Over the past years, there has been sustained research activity on the MPT's relationship with cannabis use variables (i.e. frequency, craving, severity, and related problems) [26–31], but there is substantial variability in estimated effects across studies making it unclear, which demand indices most closely map onto specific cannabis use indicators. Initial support for the MPT's concurrent validity was collected by Collins *et al*. [30] using ecological momentary assessment. In another study, Aston *et al*. [31] found that the MPT discerns between individuals with cannabis dependence symptoms and those without any symptoms. However, a recent literature review of the MPT studies [12] indicated that the legal status across countries and states, the variation in other important aspects such as product characteristics (e.g. strain type, THC), and the quality of the substance may affect purchase decisions and yield mixed results. Another challenge is the difference in the unit of consumption measure (e.g. joint, hits, and puffs) that could potentially influence the validity of the MPT. Moreover, the extent to which MPTs are valid across gender is not clear because females are underrepresented in the cannabis literature. Evidence suggests that there are significant sex-specific differences in patterns of cannabis use and consequences [32]. Although males usually report using cannabis in higher quantities and frequency than females [33, 34], the latter seem to be more sensitive to THC psychoactive effects and progress more rapidly in developing cannabis-related problems, a phenomenon known as "telescoping effect" [35, 36].

A prior meta-analysis has examined the validity of HPTs in general for measuring psychoactive substance demand, but aggregated the MPT with other HPTs [18], because of the relatively few studies at that time. A narrative review [21] has also investigated the relationship between CUD and demand, but did not look at other cannabis indicators, such as frequency and quantity or consequences, which are of value for screening, diagnostic, and intervention purposes. Since then, the literature has substantially expanded, and the present study evaluated the concurrent validity of the MPT as an indicator of cannabis demand by meta-analyzing cross-sectional effect sizes between MPT demand indices and a range of cannabis-related variables. It was also aimed at evaluating sex differences, MPT structural characteristics (i.e. number of prices), and analytic characteristics (i.e. index transformations, modeling equations) in relation to the MPT's concurrent validity. The hypothesis tested in this study was that higher cannabis reinforcing value (demand) would be associated with higher cannabis use, problems, and dependence levels. Given the dynamic cannabis legalization landscape and burgeoning use of the MPT, it is necessary to quantitatively take stock of its concurrent validity and its structural characteristics to optimize its use in quantifying cannabis demand.

METHOD

This meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA-S [37]) guidelines (see Supporting information Table S1 for the PRISMA Checklist) and was pre-registered in PROSPERO (ID: CRD42021238480).

Literature search strategy and inclusion criteria

Searches were conducted in PubMed, PsycInfo, Scopus, and Web of Science in November 2021. In electronic databases, restriction was set on peer-reviewed papers. Additionally, two preprints' repositories (i.e. PsyArXiv and BioRXiv) were checked to ensure the most recent available research was captured. The Boolean search term combinations used in the abovementioned databases were as follows: (behavioral economic OR behavioural economic OR reinforcing efficacy OR reinforcing value OR purchase task) AND (cannabis or marihuana or marijuana). Eligible studies were screened by two independent reviewers (A.G.R. and V.M.L.) with expertise in behavioral economic demand assessments in the addiction field. Eligibility criteria were as follows: (i) include human samples; (ii) provide cross-sectional correlations between MPT data and cannabis variables (i.e. frequency and quantity of use, cannabis-related problems, and dependence); and (iii) include trait-based MPT versions (i.e. assessments of general preferences for cannabis, as opposed to preferences in the moment). Studies on state demand (conducted in laboratory settings) were excluded because the instructional sets are substantively different in ways that could give rise to significant variations in demand.

The reviewers extracted relevant information from the studies included in the meta-analysis: authors (names), title (name), year of publication (year), country (name), sample characteristics (sample size, mean age and standard deviation, and sex), use of MTurk samples, task structural characteristics (number and range of prices), description of the MPT vignette (time frame, consideration

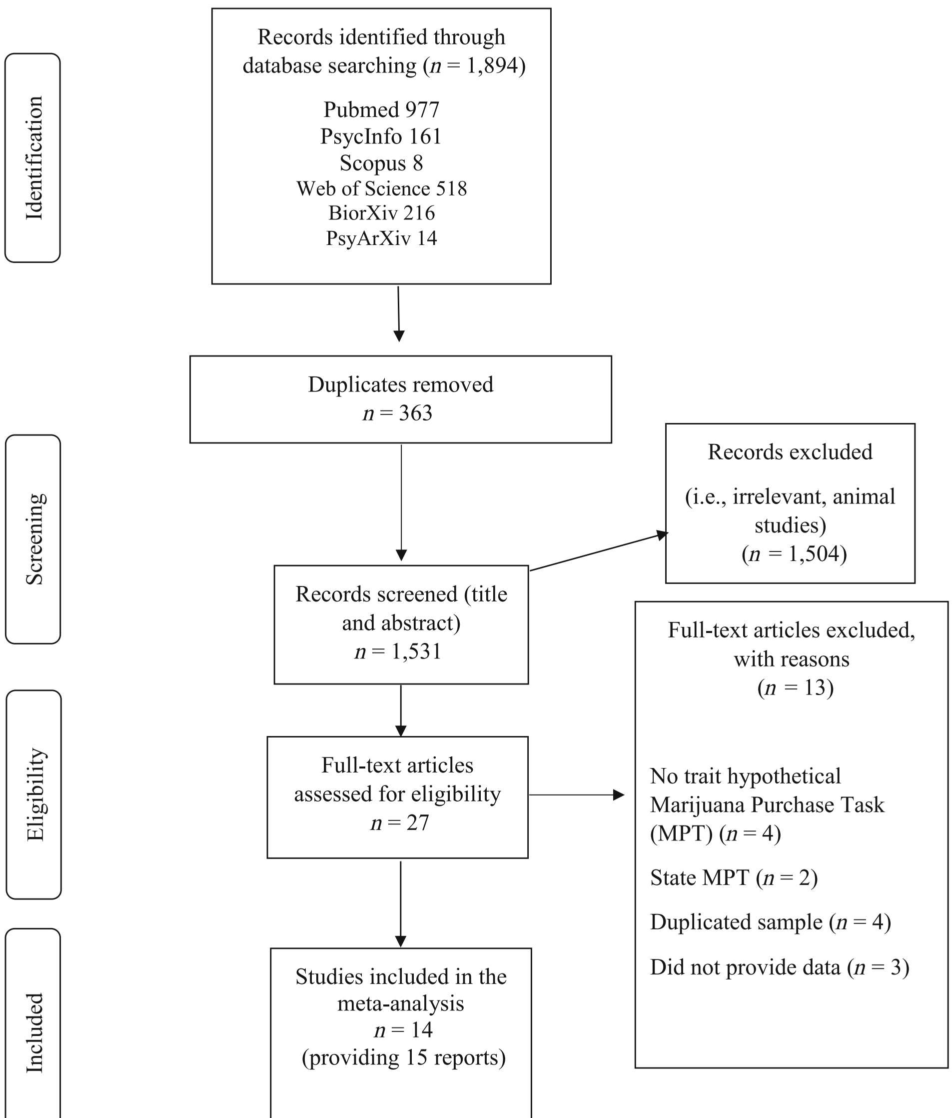

FIGURE 1 PRISMA flow-chart on the literature search procedure

of the legal status), measures of cannabis use (frequency, quantity, and problems), equation used to derive elasticity of demand (e.g. two-parameter, exponential, and exponentiated), type of index transformation (e.g. log, square-root, and cube-root), quality control procedures to correct for non-systematic MPT, and outcome measures (effect sizes for each demand and cannabis-related indicator).

A total of 1894 records were identified through databases and preprint repositories. There was not disagreement in the decision to include any particular study. After removing duplicate records, a total of 1531 studies were individually reviewed, and 27 full-text articles were assessed for eligibility (see Fig. 1 for PRISMA flowchart). A total of 14 publications, including data from 15 samples, were retained. Authors from eight studies were contacted to request data that was necessary to run the purported meta-analyses. Whenever both MPT variables and cannabis involvement indicators (frequency, quantity, problems, and dependence) were used in a paper, for a different purpose or reporting analyses, authors were asked to provide the necessary data to allow for meta-analyses. Raw data that were provided by the original authors (k = 1) underwent a data processing pipeline that is representative of the paper itself (e.g. using log-transformations if reported by authors in the original paper). Our rationale for using this approach was to adhere to existing published procedures and deviate minimally from the already published literature. To ensure standard practices in demand data processing, we used the freely available R script template "PBCAR/PurchaseTasks" to model raw data provided by Amlung and MacKillop [26]. The data processing pipeline is available on github and addresses non-systematic data, outliers, and demand curve modeling [38].

Meta-analytic approach

Pearson zero-order correlations were used as primary outcome measure in random effects meta-analyses. Magnitude of effects was interpreted as per the guidelines of Cohen *et al.* [39], where r's ≤ 0.49, r's = 0.50–0.79, and r > 0.80 are interpreted as small, medium, and large, respectively. To characterize the heterogeneity across studies, the Cochran's Q, the τ^2, and I^2 were estimated, where $I^2 \leq 25\%$, $I^2 \sim 50\%$, and $I^2 \geq 75\%$ values indicate low, moderate, and high heterogeneity across studies [40]. The 95% prediction interval was calculated as well [41, 42], as was a "jackknife" (one-study-removed) analysis, iteratively removing one study at a time (K number of studies −1) to detect studies disproportionally contributing to the overall effect sizes. A minimum of three effect sizes were required for meta-analysis, both to reflect a distribution of effect sizes and to permit jackknife analyses.

A set of mixed effects analyses using the Q statistics was performed to examine differences in effect sizes based on the categorical variables (i.e. cannabis variables, type of mathematical transformation to correct for absence of normality). Last, the effect of continuous potential moderators (average % females, and number of MPT prices) was assessed using meta-regressions at a two-sided 95% confidence level. It is important to note that the moderator effect of number of prices over the intensity estimates was not assessed, because intensity (i.e. number of prices at unrestricted costs) is not influenced by unit price. Year of publication is an extrinsic variable that a priori should not be related with the study results because it has nothing to do with the research enterprise. However, considering the reproducibility crisis it makes sense to analyze year of publication as a potential source of variability affecting the estimates over time that could be explained by inappropriate practices, such as HARKing or p-hacking [43, 44].

Methodological quality

The methodological quality of the included studies was assessed using the Analytical Cross Sectional Studies Critical Appraisal Tool designed by JBI [45]. This scale comprises eight items that inform on whether a study has addressed the possibility of bias in its design, conduct, and analysis. Answer options include "yes," "no," "unclear," or "not/applicable." Two assessors (A.G.R. and V.M.L.) appraised the quality of the reviewed studies individually. We used a consensus-based approach, meaning disagreements were discussed between reviewers. Given the purpose and methodological approach of the included papers (i.e. correlational and exploratory), only six items of eight were evaluated. For each individual study, poor methodological quality was considered if ≤50% of "yes" items (i.e. 2/6) were rated.

Publication bias

There is no single valid assessment of publication (small study) bias [46], so a combination of indicators was used: (i) the fail-safe N statistic, which estimates the number of missing studies (i.e. zero effect) that would need to be added to the meta-analysis to yield non-significant overall effects. N values lower than $5k + 10$ (k = number of included studies) were used as suggestive of concerns [47]; (ii) the two-tailed Begg-Mazumdar test (i.e. rank correlation between the standard effect size and their variances, with deviations from zero indicating the presence of publication bias); (iii) the two-tailed Egger's test (i.e. effect size divided by its standard error), which indicates if there are small studies disproportionately contributing to large effect sizes; and (iv) Tweedie's trim and fill approach, which detects the number of estimated missing studies and readjust the effect sizes after its imputation. As a further publication bias assessment, we also looked at the effect of year of publication on the overall effect sizes.

RESULTS

Descriptive characteristics of the studies

Table 1 presents a summary of the reviewed studies. A total of 14 publications (15 distinct samples) were included in the meta-

TABLE 1 Study characteristics k = 14

Study	Country	Sample size	Mturk sample (yes/no)	Sex (% females)	Age M (SD)	Structural MPT characteristics: No. prices	Structural MPT characteristics: Unit of purchase	Structural MPT characteristics: Price range	Cannabis-related measures: Frequency cannabis use	Cannabis-related measures: Quantity cannabis use	Cannabis-related measures: Cannabis-related problems	Cannabis-related measures: Cannabis dependence
Amlung and MacKillop [26]	Canada	289	No	40.10	31.70 (9.90)	20	Grams[c]	CAD$0–60	–	–	–	CUDIT-R
Aston et al. [31]	USA	99	No	37.40	21.40 (4.40)	22	Hits (1 joint = 0.9 g)	$0–10	% days/60 days[d]	–	–	DSM-IV
Dolan et al. [19]	USA	515	Yes	43.9	34.1 (9.5)	16	Hits (1 joint = 0.09 g)	$0.25–10	Past 30-day cannabis use days	Grams/day	–	CUDIT
Fergusson et al. [9]	USA	186	Yes	40.3	33.59 (8.50)	22	Original MPT = hits (1 joint = 0.9 g)	$0–10	–	–	MPI	–
Greenwald et al. [20]	USA	119	No	37	44.8 (9.7)	7	No. of 0.1-oz marijuana units	$5–100	Use episodes/90 days	–	–	DSM 5
McIntyre-Wood et al. [50]	Canada	324	No	44.80	33.25 (11.27)	20	Grams	CAD$0–60	–	–	–	CUDIT-R
Minhas et al. [48]	USA	265	No	49.1	22.57 (1.07)	20	Grams	$0–60		–	MACQ	CUDIT-R
	Canada	396	No	48.5	21.41 (1.19)	20	Grams	CAD$0–60	–			
Naudé et al. [49]	USA	185[a]	No	81.00	19.96 (3.14)	20	Grams	$0–60	–	–	–	CUDIT-R
Patel and Amlung [51]	USA	733	Yes	53.20	33.70 (10.20)	20	Grams	$0–60	–	–	–	CUDIT-R
Sholler et al. [52]	USA	179	Yes	35.20	34.9 (10.10)	7	Grams	$1–100	Past 90-day use of cannabis	–	–	CUDIT-R
Strickland et al. [53]	USA	71	Yes	50.70	30.50 (7.80)	13	Hits (0.09 g/1/10th of a 0.9 g size joint)	$0–11	Days/month	Grams/week	–	DSM-IV
Strickland et al. [29]	USA	76	Yes	63.90	34.00 (8.00)	17	Hits (1 joint = 0.9 g)	$0–20	Days/month	Grams/week	–	DSM-5
Teeters et al. [28]	USA	132	No	53.80	19.89 (3.23)	20	Hits (1 joint = 0.9 g)	$0–10	Days/month[c]	–	The modified MPI	–
Vincent et al. [10]	USA	683[b]	No	16.00	21.20 (2.20)	9	Joints (0.5 g/10 puffs)	$0–20	–	Grams/week	–	–

Abbreviations: CUDIT-R, Cannabis Use Dependence Identification Test-Revised; DSM, Diagnostic and Statistical Manual of Mental Disorder; MACQ, The Marijuana Consequences Questionnaire; MPI, The Rutgers Marijuana Problems Index; MPT, The Marijuana Purchase Task; USA, United States of America.

[a]The subsample of 85 dual users (cannabis + alcohol) was used.

[b]The subsample of 608 high-grade marijuana users was used.

[c]The MPT assessing hypothetical illegal cannabis consumption was considered in the meta-analysis.

[d]Timeline follow-back.

analyses. All the included studies were published between 2015 and 2022. The median sample size used across meta-analyzed studies was 186 (range = 71–733), and weighted average age across participants was 29.08 (SD = 6.82) years. Females comprised 16% to 81% of the samples, with a weighted percentage of 42.68%. Most samples (*k* = 12/15; 80%) were recruited in the United States and the remaining three (20%) in Canada. Six of 15 reports [10, 28, 31, 48, 49] included community young adult samples (i.e. 19.89–22.57 years old), two [26, 50] included adult samples recruited from the community, six additional [9, 19, 29, 51–53] included crowdsourced MTurk samples, and the remaining one included a clinical sample of HIV + cannabis users [20].

Seven studies provided data on frequency of cannabis use [19, 20, 28, 29, 31, 52], four reported on past-month cannabis use [19, 28, 29, 53], one additional assessed cannabis use within the past 2 months [31], and the remaining two examined cannabis use within the past 3 months [20, 52]. Quantity of cannabis use was assessed in four studies, with grams per week (3/15) [10, 29, 53] the most frequently reported measure, followed by grams/day [19]. Cannabis problems were assessed by the Marijuana Consequences Questionnaire (MACQ) [48] and the Marijuana Problem Index (MPI) [9, 28]. With regard to the assessment of cannabis dependence severity, four studies used Diagnostic and Statistical Manual of Mental Disorders (DSM)-IV/5 criteria [20, 29, 31, 53], and seven additional relied on the Cannabis Use Dependence Identification Test-Revised (CUDIT) [19, 26, 48–52].

The structural characteristics of MPTs varied substantially in terms of the number of prices (range = 7–22), units of purchase (hits/puffs, *k* = 6/15 reports; grams, *k* = 7/15; joints, *k* = 1/15; 0.1-oz cannabis units, *k* = 1/15), and maximum price per unit (range = $0–100). Except for the illegal demand assessment in the study by Amlung and MacKillop [26], none of the reviewed works specified whether cannabis was legal versus illegal or for recreational versus therapeutic use. Of note, one study [52] assessed demand for sativa and indica varieties.

Methods to control for non-systematic data were relatively common, with 12/15 (80%) reporting some sort of data quality control, with

TABLE 2 Effect sizes and heterogeneity on the associations between cannabis demand, cannabis use frequency, quantity, cannabis-related problems, and cannabis dependence

Demand index	k	n	r_{RE}	95% CI	P	rOSR	Q	P_Q	I^2	τ^2	95% PI
Frequency											
Intensity	8	1167	0.258	0.117, 0.388	**<0.001**	0.236, 0.300	36.423	<0.001	80.781	0.034	−0.218, 0.635
O_{max}	3	285	0.182	0.040, 0.317	**0.013**	0.116, 0.254	2.961	0.227	32.463	0.005	−0.805, 0.901
P_{max}	3	289	−0.122	−0.235, −0.005	**0.040**	−0.171, −0.098	1.423	0.491	0	<0.001	−0.708, 0.564
Breakpoint	3	289	0.031	−0.092, 0.153	0.623	−0.016–0.079	2.218	0.330	9.815	0.001	−0.697, 0.728
Elasticity (α)	8	1150	−0.147	−0.261, −0.029	**0.014**	−0.186, −0.120	23.457	0.001	70.158	0.019	−0.475, 0.217
Quantity											
Intensity	4	1256	0.325	0.210, 0.430	**<0.001**	0.271, 0.397	10.102	0.018	70.303	0.010	−0.168, 0.688
O_{max}	-	-	-	-	-	-	-	-	-	-	-
P_{max}	-	-	-	-	-	-	-	-	-	-	-
Breakpoint	-	-	-	-	-	-	-	-	-	-	-
Elasticity (α)	4	1250	−0.177	−0.356, 0.015	0.070	−0.275, −0.081	25.914	<0.001	88.423	0.031	−0.781, 0.598
Cannabis-related problems											
Intensity	4	964	0.173	−0.008, 0.343	0.061	0.107, 0.254	22.954	<0.001	86.931	0.030	−0.586, 0.770
O_{max}	4	960	0.216	0.097, 0.329	**<0.001**	0.159, 0.254	10.098	0.018	70.292	0.011	−0.296, 0.631
P_{max}	4	964	0.165	0.013, 0.310	**0.034**	0.101, 0.205	16.178	0.001	81.456	0.020	−0.485, 0.697
Breakpoint	4	964	0.226	0.118, 0.329	**<0.001**	0.191–0.275	8.464	0.037	64.556	0.008	−0.222, 0.595
Elasticity (α)	4	957	−0.191	−0.421, 0.063	0.140	−0.273, −0.088	44.772	<0.001	93.299	0.063	−0.887, 0.771
Cannabis dependence											
Intensity	13	3134	0.305	0.215, 0.390	**<0.001**	0.284, 0.335	78.216	<0.001	84.658	0.025	−0.049, 0.591
O_{max}	7	1976	0.320	0.192, 0.438	**<0.001**	0.276, 0.361	48.816	<0.001	87.709	0.028	−0.134, 0.663
P_{max}	8	2193	0.128	0.051, 0.204	**0.001**	0.107, 0.154	20.099	0.005	65.172	0.008	−0.110, 0.352
Breakpoint	7	1976	0.199	0.082, 0.310	**0.001**	0.159, 0.245	36.085	<0.001	87.372	0.020	−0.191,0.535
Elasticity (α)	12	2328	−0.303	−0.419, −0.177	**<0.001**	−0.334, −0.274	106.850	<0.001	89.705	0.048	−0.677, 0.196

Note: Hyphens indicate that meta-analyses could not be performed because of low number of observations (*k* < 3). Bold values denote statistically significant results.

Abbreviations: I^2, proportion of variation across studies because of heterogeneity; *k*, number of studies; *n*, sample size; P_Q, *P* value corresponding to Cochran's *Q*; Q, Cochran's *Q* test of homogeneity; r_{RE}, effect size statistic from the random effects model; rOSR, range of effect sizes from one study removed; τ^2, tau-square (variance of the mean effect); 95% CI = 95% confidence interval; 95% PI, 95% prediction interval.

the Stein *et al*. [54] criteria the most widely used (10/15; 66.66%). A total of four of 13 studies reported data on elasticity using the exponential Hursh and Silberberg equation [19, 31, 49, 52], 1/13 used the Hursh and Winger [20] equation, 6/13 used the "exponentiated" modeling of demand by Koffarnus *et al*. [26, 28, 29, 48, 50, 53] (including data modeled through the R template), and 1/15 the Yu *et al*. [10] non-lineal mixed effects model. The remaining one did not specify which equation was used to calculate elasticity [9].

Cross-sectional relationships between the MPT and cannabis-related indicators

Table 2 includes meta-analyses of cross-sectional associations between MPT demand indicators and cannabis use variables. Statistically significant aggregate effect sizes ranged between $|r$'s$|$ = 0.122–0.325. Overall (with the exception of O_{max}, P_{max}, and breakpoint in relationship to frequency of cannabis use), high heterogeneity was observed across MPT estimates. Forests plots for each cannabis indicator are provided in Supporting Information Fig. S1–S17. Demand indices were significantly related to most of the cannabis variables, except for the associations for breakpoint with frequency of cannabis use, the elasticity and quantity associations, and intensity and elasticity with cannabis-related problems.

Intensity

Pooled estimates showed that the effect sizes for intensity (*rs* = 0.173–0.325) were not statistically significantly different across cannabis indicators. Demand unit measurement (hit$_{(k = 14)}$ vs grams$_{(k = 12)}$) did not significantly influence the observed estimates. However, demand indices' mathematical transformations (log-transformed$_{(k = 14)}$ vs non-transformation$_{(k = 9)}$, vs square-root$_{(k = 5)}$ vs Z-score transformation$_{(k = 1)}$) did significantly impact the observed estimates ($Q_{(3)}$ = 22.293, P < 0.001). Specifically, higher effect size estimations were observed for studies using non-transformations (r = 0.301, 95% CI = 0.225, 0.374) compared with log-transformed (r = 0.298, 95% CI = 0.203, 0.388), square-root (r = 0.271, 95% CI = 0.166, 0.370), and Z-scores (r = −0.070, 95% CI = −0.212, 0.075).

O_{max}

The effect sizes for O_{max} (r = 0.182–0.320) were not statistically significantly different across cannabis indicators ($Q_{(2)}$ = 2.390, P = 0.303). Demand unit measurement (hit$_{(k = 7)}$ vs grams$_{(k = 7)}$) did significantly impact the O_{max} estimates ($Q_{(1)}$ = 7.645, P = 0.006), with studies using grams (r = 0.349, 95% CI = 0.238, 0.451) versus hits (r = 0.164, 95% CI = 0.093, 0.233) reporting greater effect sizes. MPT indices' transformations (log-transformed$_{(k = 6)}$ versus non-transformation$_{(k = 6)}$, versus square-root$_{(k = 1)}$, versus Z-score$_{(k = 1)}$) did not affect the observed effect sizes.

P_{max}

The effect sizes for P_{max} (r = −0.122–0.165) differed across indicators ($Q_{(2)}$ = 14.071, P < 0.001), with studies reporting estimates for problems and severity showing higher effect sizes than frequency. Unit measurement (hit$_{(k = 7)}$ vs grams$_{(k = 8)}$) did not significantly influence the observed estimates. There were differences in effect sizes as a function of MPT demand transformation ($Q_{(3)}$ = 20.259, P < 0.001), with higher effect sizes being observed if Z-scores were used ($r_{(k = 1)}$ = 0.390, 95% CI: 0.261, 0.506), as compared with log-transformations ($r_{(k = 4)}$ = 0.062, 95% CI = −0.106, 0.226), non-transformation ($r_{(k = 7)}$ = 0.105, 95% CI = 0.029, 0.180), and square-root use ($r_{(k = 3)}$ = −0.024, 95% CI = −0.163, 0.115).

Breakpoint

The effect sizes for breakpoint ranged between 0.031 and 0.226 and significantly differed across indicators ($Q_{(2)}$ = 6.164, P = 0.046). Statistically significant effects were only observed for problems and severity (Table 2). Unit measurement of cannabis use (hit vs grams) significantly influenced the breakpoint estimates ($Q_{(1)}$ = 9.450, P = 0.002), with MPT studies using grams reporting higher effect sizes ($r_{(k = 7)}$ = 0.273, 95% CI = 0.202, 0.341) compared with those using hits ($r_{(k = 7)}$ = 0.055, 95% CI = −0.066, 0.175). Across cannabis indicators, there were significant differences ($Q_{(3)}$ = 11.285, P = 0.010) as a function of MPT index transformation, with effect sizes being higher if Z-scores were used ($r_{(k = 1)}$ = 0.300, 95% CI = 0.163, 0.426) than those observed for the remaining index-level transformations (non-transformed: $r_{(k = 6)}$ = 0.231, 95% CI = 0.142, 0.316; log-transformed: $r_{(k = 4)}$ = 0.133, 95% CI = −0.082, 0.337; square-root: $r_{(k = 3)}$ = 0.033, 95% CI = −0.078, 0.144).

Elasticity

The effect sizes for elasticity (|0.147–0.303|) across cannabis use indicators were not statistically significantly different ($Q_{(3)}$ = 3.406, P = 0.333). Studies using grams ($r_{(k = 11)}$ = −0.402, 95% CI = −0.476, −0.322) as unit measurement reported greater effect sizes as compared with those using hits ($r_{(k = 14)}$ = −0.140, 95% CI = −0.205, −0.075) ($Q_{(1)}$ = 24.410, P < 0.001). The use of log-transformations ($r_{(k = 14)}$ = −0.293, 95% CI = −0.425, −0.148) resulted in higher magnitude of effects relative to natural-log transformed values ($r_{(k = 7)}$ = −0.231, 95% CI = −0.318, −0.140) ($Q_{(5)}$ = 15.478, P = 0.009). The use of exponential ($r_{(k = 10)}$ = −0.199, 95% CI = −0.268, −0.127) versus "exponentiated" equations ($r_{(k = 14)}$ = −0.331, 95% CI = −0.425,

TABLE 3 Moderation effects of sex and number of prices used in the Marijuana Purchase Task (MPT) over the observed estimates by cannabis variable

	Sex				MPT prices				Year of publication[a]		
Demand indicator	**Coefficient**	**SE**	**95% CI**	**P**	**Coefficient**	**SE**	**95% CI**	**P**	**Coefficient**	**SE**	**P**
Frequency											
Intensity	0.005	0.008	−0.010, 0.021	0.482	–	–	–	–	−0.010	0.041	0.807
Elasticity (α)	−0.0001	0.006	−0.013, 0.013	0.983	0.004	0.011	−0.017, 0.027	0.670	−0.001	0.034	0.971
Quantity											
Intensity	0.005	0.004	−0.003, 0.014	0.238	–	–	–	–	0.020	0.099	0.834
Elasticity (α)	−0.009	0.004	−0.017, −0.0007	**0.034**	−0.029	0.040	−0.107, 0.049	0.467	−0.089	0.125	0.474
Cannabis-related problems											
Intensity	0.025	0.016	−0.006, 0.056	0.115	–	–	–	–	−0.037	0.124	0.762
O_{max}	−0.006	0.015	−0.036, 0.023	0.673	0.011	0.087	−0.159, 0.183	0.894	0.052	0.082	0.520
P_{max}	−0.030	0.008	−0.046, −0.014	**0.0002**	0.155	0.041	0.074, 0.235	**0.0002**	0.074	0.102	0.463
Breakpoint	−0.017	0.011	−0.039, 0.004	0.121	0.054	0.076	−0.095, 0.204	0.476	0.133	0.049	**0.007**
Elasticity (α)	−0.015	0.028	−0.070, 0.039	0.569	0.170	0.122	−0.069, 0.409	0.164	−0.081	0.162	0.616
Cannabis dependence											
Intensity	−0.003	0.004	−0.012, 0.004	0.411	–	–	–	–	0.033	0.030	0.275
O_{max}	−0.008	0.005	−0.018, 0.001	0.099	0.041	0.057	−0.071, 0.154	0.472	0.057	0.030	0.060
P_{max}	−0.003	0.003	−0.010, 0.003	0.374	0.022	0.040	−0.056, 0.101	0.570	0.030	0.023	0.189
Breakpoint	−0.007	0.004	−0.016, 0.002	0.124	0.053	0.050	−0.045, 0.152	0.289	0.042	0.029	0.154
Elasticity (α)	0.003	0.005	−0.007, 0.014	0.532	−0.010	0.011	−0.033, 0.012	0.367	−0.055	0.037	0.139

Note: Moderation analyses were not conducted for the O_{max}, P_{max}, and breakpoint indicators in relation to frequency and quantity of cannabis use because of an insufficient number of observations ($k \leq 3$). Bold values denote statistically significant results.
Abbreviations: SE, standard deviations; 95% CI, 95% confidence interval.
[a]Meta-regressions on year of publication were conducted in instances where at least three observations were provided.

−0.229) resulted in significantly lower elasticity estimates ($Q_{(1)}$ = 4.436, P = 0.035).

Moderation analyses by sex and number of MPT prices

Moderation analyses are reported in Table 3. Female sex significantly moderated the relationship between elasticity and quantity of cannabis use and between P_{max} and cannabis problems. Significant moderating effects suggested that these relationships are strengthened with increasing male representation. Higher number of MPT prices was significantly associated with larger effect sizes for the P_{max} and cannabis problems associations. Last, there was a small impact of year of publication and more recent studies informed on higher effect sizes for the relationship between breakpoint and cannabis-related problems.

Methodological quality

The methodological quality of the studies is reported on the Supporting information Appendix S1. Overall, there was evidence of good methodological quality. Of 14 studies, 12 met all requirements and two met 87.5%. The slightly lower scores were because of missing information about inclusion/exclusion criteria and description of the study subjects and setting.

Publication bias

Analyses suggested minimal impact of publication bias across cannabis use indicators (Table 4). The Fail-safe analyses indicated that the number of studies that would be required to nullify the effect for the cannabis use frequency indicator would be between 1 and 96, for quantity of cannabis use between 10 and 103, for problems 22 and 48, and for dependence 64 and 909. The Mazumdar rank correlation tests did suggest bias for the P_{max} and cannabis dependence relationship and the Egger regression suggested small publication bias for the intensity-quantity and frequency associations and P_{max} and cannabis dependence. The Trim-and-Fill approach suggested one potentially missing study for the relationship between intensity and quantity of cannabis use and three for the intensity and frequency estimates. Nonetheless, effect sizes were not changed substantially after an imputed value was included (intensity-frequency: $r_{(before)}$ = 0.258; $r_{(after)}$ 0.195; intensity-quantity: $r_{(before)}$ = 0.325; $r_{(after)}$ = 0.285) .

DISCUSSION

Results of this meta-analysis revealed statistically significant associations across in the aggregated relationships, largely supporting the concurrent validity of the MPT. Except for P_{max} and breakpoint, there was no evidence of differences by cannabis indicators, meaning generally similar performance of the MPT in terms of criterion validity. Of

TABLE 4 Publication bias assessment

	Classic fail-safe N		Begg and Mazumdar rank correlation		Egger's regression intercept			Tweedie's trim and fill
Demand indicator	N P > α	P	τ	P	Intercept	SE	P	N trimmed
Intensity	96	<0.001	0.464	0.107	5.667	0.337	<0.001*	3
O_{max}	5	0.002	<0.001	1.00	4.410	9.843	0.731	0
P_{max}	1	0.038	<0.001	1.00	−1.926	6.717	0.822	0
Breakpoint	0	0.667	<0.001	1.00	−6.262	6.072	0.490	0
Elasticity (α)	32	<0.001	−0.535	0.063	−1.668	1.746	0.376	0
Intensity	103	<0.001	0.500	0.308	3.497	0.500	0.019*	1
Elasticity (α)	10	<0.001	−0.833	0.089	−4.834	2.165	0.155	0
Intensity	30	<0.001	−0.166	0.734	−6.174	6.398	0.436	0
O_{max}	44	<0.001	−0.166	0.734	−4.591	3.847	0.355	0
P_{max}	22	<0.001	<0.001	1.00	1.032	6.461	0.887	0
Breakpoint	48	<0.001	−0.500	0.308	−5.146	2.980	0.226	0
Elasticity (α)	45	<0.001	0.500	0.308	12.177	5.903	0.175	0
Intensity	909	<0.001	−0.192	0.360	−0.579	1.891	0.765	0
O_{max}	405	<0.001	−0.476	0.133	−3.618	2.656	0.231	0
P_{max}	64	<0.001	−0.750	0.009*	−3.441	1.114	0.021*	0
Breakpoint	156	<0.001	−0.571	0.071	−4.030	1.975	0.096	0
Elasticity (α)	739	<0.001	0.287	0.192	3.799	2.418	0.147	0

Note: Hyphens indicate that publication bias assessments could not be performed because of low number of observations (k < 3).
Abbreviation: SE, standard error.
*Indicates significant effects.

the demand indices, intensity, O_{max}, and elasticity were the most robustly associated with all, except cannabis use problems. Higher male sex representation produced increased magnitudes of effects for elasticity-quantity and P_{max}-problems. There was also evidence of moderating effects by number of MPT prices and particular mathematical transformation to correct for normality deviations. Last, small effects of publication bias and adequate methodological quality were found. This finding may be arguably accounted by the multiple sources of heterogeneity detected; particularly, vignettes used in the tasks and methodological approaches to correct for outliers and sample characteristics.The meta-analyses yielded support for the concurrent validity of the MPTs, although with substantial heterogeneity, probably stemming from variability in measurement of cannabis units, experimental vignettes, and number of prices used, and differences in methodological procedures to calculate cannabis demand. Of note, larger effects sizes were present for intensity, O_{max}, and elasticity, whereas smaller effect sizes were observed for P_{max} and breakpoint, which aligns with meta-analyses conducted with purchase tasks based on other commodities [14–18]. If we consider the high variability in unit measurement across MPTs used at present (i.e. joints, hits, and grams), it is worth noting that the concurrent validity of all indices, except intensity and P_{max}, seems superior if grams versus hits are considered, reflecting real-world purchase scenarios more accurately, which supports prior findings from a qualitative study in regular cannabis users [55].

In terms of specific indicators, it can be concluded that intensity, O_{max}, and elasticity are the most robust MPT indicators in relation to cannabis use. Levels of consumption at zero cost (i.e. intensity) are not a function of economic constraints, and given that cost is a proxy of both pricing and drug accessibility [56], it can be inferred that intensity is more accurately reflecting overall cannabis motivational appetite than other demand indicators. This finding is well aligned with higher consumption in a natural environment where cannabis may be widely available and easy to obtain. Moreover, O_{max} may be argued to be more tied to intrinsic drug motivating strength and associated costs [57], reflecting the most expenditure (output) the individual will accept in cannabis consumption. It was notable that elasticity exhibit robust associations, especially with cannabis dependence, and reflects the most canonical indicator of reinforcing values insofar as it measures sensitivity to increasing response costs [56].

Higher inclusion of female samples across studies was related to decreased relationships between elasticity of demand and quantity of cannabis use, P_{max}, and cannabis problems. Women show greater sensitivity to the effects of THC and cannabinoids [58], which arguably may account for the lower cannabis use levels observed in the literature [33, 34]. Considering this fact, it may occur that women may obtain the same effect with lower levels of consumption, which decreases the relevance of price and could potentially account for the lower effect sizes in the quantity and elasticity associations. Regarding P_{max}-problems, because females are particularly vulnerable to mood and anxiety-related conditions [58, 59], it may be possible that problems associated to cannabis use and those associated to mental health issues are confounded, leading to inconsistent associations (therefore, decreasing the effect size) between P_{max} and problems. This does not happen in dependence, because "symptoms" clearly map onto cannabis use.

The concurrent validity of the P_{max} was particularly sensitive to the number of prices used in MPTs, as evidenced by the significant moderating effects in the relationship between P_{max} and cannabis problems. This finding may explain in part the relatively lower effect sizes observed for P_{max} as compared with the remaining indicators. As the latter MPT index is intrinsically influenced by price density [60], respondents who are heavier cannabis users may not reach breakpoint levels if low costs per unit are considered, which may produce unreliable P_{max} estimates. There are no empirical assessments of the influence of price density on the MPT demand indices, but research conducted with other commodities suggests that excessively low prices may produce ceiling effects, whereas extremely high prices (e.g. \$1000/g) may turn into unrealistic demand [61, 62]. Although a 17-price purchase task seems preferable [62], the impact of both the number and range of prices used over the task reliability needs to be further examined.

Last, there was some evidence of the impact of year of publication on the relationship between breakpoint and cannabis-related problems. Recent studies are increasingly using demand transformations to correct for outliers with significant variation in the type of transformation used, with breakpoint amongst the ones with more variability (none vs raw indices, log, or square-root) in terms of the used transformations. In addition, in the last 2 years, studies have increasingly used samples with a more frequent pattern of cannabis use, therefore potentially influencing the higher estimates for the breakpoint and cannabis-related indicators. These studies included active users testing positive for THC. Further, most recent studies (published in 2021) vary in the vignettes used, whereas Greenwald *et al.* [20] instruct participants to indicate the units they would purchase over a 24-h period, and others consider a 1-week period [48, 48, 50].

To foster evidence-based practices and yield comparable findings, MPT studies should consider systematically reporting key experimental features, including the timeframe of use, the cannabis quality (i.e. low, average, and high), and source of administration (e.g. combustibles, edibles). Given the substantial variability across studies in terms of procedural methods to correct for absence of normality, researchers are encouraged to provide a clear rationale to support their decision to adopt a particular index transformation and minimize bias. Developing reporting guidelines, akin to PRISMA guidelines for meta-analyses to contribute to standardized practices and enhance replicability, is warranted. An example of such a guideline checklist is provided in Supporting information Appendix S2.

Some limitations are acknowledged. First, the generalizability of the findings pertaining to MPT validity might be limited to other countries different than United States and Canada, given that virtually all the studies were conducted in North America. Second, because of the insufficient number of studies informing on the quality of cannabis (i.e. low, moderate, and high), moderation analyses could not be completed. In addition, the relationship between breakpoint, O_{max}, P_{max}, and quantity of use was not often assessed, so this precluded them from being included in the meta-analyses. Third, only one of the reviewed studies included a clinical sample [20] and differences based on the presence of other psychiatric disorders could not be examined. More severe patterns of use and higher impacts in terms of physical/mental wellbeing have been noted in specific samples, such as pregnant women and people with psychosis [63]. These populations are underrepresented in the behavioral economic cannabis literature, and more studies conducted in vulnerable populations would be needed. More generally, given the high heterogeneity observed, caution should be considered when interpreting the results because it is also possible that both over- and underestimations may exist. Relatedly, subgroup analyses (e.g. concurrent validity by cannabis use indicator or measure) would have been more informative and appropriate, but the number of studies made this pipeline non-viable.

The most important overall finding of this study is evidence that MPT demand indicators are generally meaningfully associated with clinically relevant cannabis use indicators, especially intensity, O_{max}, and elasticity. Notwithstanding the above, we found small magnitudes of effects, well above high heterogeneity, across MPT indicators and cannabis involvement. The etiology of CUD is multi-factorial [64], and small effect sizes may be reflecting some other determinants such as contextual (accessibility and availability), but also, individual (anxiety, depression) factors [65]. Relatedly, cannabis use motives (fundamentally enhancement and coping) seem to predict increased cannabis-related problems in those with elevated cannabis demand [11]. An intriguing avenue for future research will be to examine how behavioral economics of cannabis demand can inform longitudinal changes in cannabis involvement and how this differs by population group (e.g. clinical vs general populations).

Finally, these findings support use of the MPT in clinical fields and cannabis regulatory science to better understand the relationship between cannabis consumption preferences, intersections with alternative commodities (i.e. substitutes or complementary reinforcers) and policy-related domains, including price/taxation, substitutability, and marketing/labeling of cannabis use. From a clinical standpoint, MPT has use to examine mechanisms of treatment response (changes in reinforcement value) and optimize intervention parameters most likely to produce changes in behavior. Purchase tasks can inform on populations most likely to respond (attain abstinence) and aid the refinement of intervention parameters, as shown by several behavioral economic studies [66, 67].

Regarding public health applications, cannabis markets share some common characteristics with markets of other goods, such as tobacco and alcohol. In this study, an increase in price of 10% would predictively lead to a decrease in up to a 3% in consumption. Importantly, the MPT has interest as most of the environmental and community mass-media prevention campaigns are not evaluated. Using these tasks can offer a multi-dimensional assessment of policies "impact over the global population," because changes in the simple annual prevalence rate will not fully reflect changes in the distribution of users or the amount consumed in total. Prevalence rates represent the behavior of light and casual users and discount the behavior of regular and heavy users, who generally represent a much smaller proportion of the total users, although they represent the majority of quantity consumed [68]. Given dramatic changes in cannabis legalization, particularly in the United States, the validity of measures that permit experimental regulatory science is relevant and indeed essential.

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DECLARATION OF INTERESTS

J. MacKillop is a principal in a private company (BEAM Diagnostics) and a consultant to Clairvoyant Therapeutics, but no commercial products fall within the scope of the review. No other authors have declarations.

AUTHOR CONTRIBUTIONS

Alba González-Roz: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; validation; writing-original draft; writing-review and editing. **Victor Martinez-Loredo:** Data curation; formal analysis; investigation; methodology; writing-review and editing. **Elizabeth Aston:** Supervision; validation; writing-review and editing. **Jane Metrik:** Supervision; validation; writing-review and editing. **James G. Murphy:** Supervision; validation; writing-review and editing. **Iris Balodis:** Supervision; writing-review and editing. **Roberto Secades-Villa:** Supervision; validation; writing-review and editing. **Kyla Belisario:** Methodology; validation; writing-review and editing. **James MacKillop:** Conceptualization; funding acquisition; investigation; methodology; project administration; supervision; validation; writing-original draft; writing-review and editing.

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