Drug and Alcohol Dependence 238 (2022) 109531

Contents lists available at ScienceDirect

Drug and Alcohol Dependence

journal homepage: www.elsevier.com/locate/drugalcdep

Age differences in the behavioural economics of cannabis use: Do adolescents and adults differ on demand for cannabis and discounting of future reward?

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ARTICLE INFO

Keywords:
Cannabis
Delay discounting
Marijuana purchase task
Adolescent

ABSTRACT

Background: Adolescence is a period of psychological and neural development in which harms associated with cannabis use may be heightened. We hypothesised that adolescent who use cannabis (adolescentsWUC) would have steeper delay discounting (preference for immediate over future rewards) and greater demand (relative valuation) for cannabis than adults who use cannabis (adultsWUC).

Methods: This cross-sectional study, part of the 'CannTeen' project, compared adultsWUC (n = 71, 26–29 years old) and adolescentsWUC (n = 76, 16–17 years old), and gender- and age-matched adolescent (n = 63) and adult (n = 64) controls. AdolescentsWUC and adultsWUC used cannabis 1–7 days/week and were matched on cannabis use frequency (4 days/week). The Monetary Choice Questionnaire assessed delay discounting. A modified Marijuana Purchase Task (MPT) assessed cannabis demand in adolescentsWUC and adultsWUC. The MPT yielded five indices: intensity (amount of cannabis used at zero cost), O_{max} (total peak expenditure), P_{max} (price at peak expenditure), breakpoint (cost at which cannabis demand is suppressed to zero) and elasticity (degree to which cannabis use decreases with increasing price). Analyses were adjusted for covariates of gender, socioeconomic status, other illicit drug use.

Results: Both adolescentsWUC and adultsWUC had steeper delay discounting than controls (F, (1,254)= 9.13, p = 0.003, η_p^2= 0.04), with no significant age effect or interaction. AdolescentsWUC showed higher intensity (F, (1,138)= 9.76, p = 0.002, η_p^2= 0.07) and lower elasticity (F, (1,138)= 15.25, p < 0.001, η_p^2= 0.10) than adultsWUC. There were no significant differences in P_{max}, O_{max} or breakpoint.

Conclusion: Individuals who use cannabis prefer immediate rewards more than controls. AdolescentsWUC, compared to adultsWUC, may be in a high-risk category with diminished sensitivity to cannabis price increases and a greater consumption of cannabis when it is free.

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https://doi.org/10.1016/j.drugalcdep.2022.109531
Received 13 November 2021; Received in revised form 28 April 2022; Accepted 29 April 2022
Available online 9 June 2022

1. Introduction

Cannabis is one of the most commonly used recreational drugs worldwide, with an estimated 3.8% of the world population reporting past-year use (United National Office on Drugs and Crime, 2020). The prevalence of past-year use is higher amongst adolescents: 22.5% of 15-year-olds in England (NHS-Digital, 2018) and 28% of 15–16-year-olds in the USA (National Institute on Drug Abuse, 2020). Earlier initiation is linked with later-life higher frequency of use (Millar et al., 2021). Notably, initiation of cannabis use before age 18 has been associated with higher prevalence of cannabis use disorder (CUD) within 12 months of use (Chen et al., 2009; Han et al., 2019; Volkow et al., 2021). There is evidence that frequent use in those under 18 confers greater risk that CUD symptoms will persist to later adulthood (Leung et al., 2020; Rioux et al., 2018).

Adolescence represents an extended period of psychological and neural development (Blakemore and Choudhury, 2006; Giedd et al., 1999), corresponding to changes in executive functioning involved in decision-making and impulse control (Blakemore and Robbins, 2012). Cannabis has a range of effects on cognition (Volkow et al., 2016) and exposure to cannabis in early adolescence may negatively impact cognitive development (Camchong et al., 2017; Churchwell et al., 2010; Lovell et al., 2020; Lubman et al., 2015; Medina et al., 2007). Age differences in decision-making, reward valuation, and executive control (Shulman et al., 2016) may lead adolescents to use greater amounts of cannabis.

Differences in cannabis use behaviour and decision-making between adolescents and adults can be examined through behavioural economics, which applies psychological and economic concepts to examine individuals' decision-making (Bickel et al., 2014). From behavioural economics comes the concept of Reinforcer Pathology, a framework for understanding decision-making that may contribute to the development of substance use disorders. This posits that problematic substance use can arise from persistently high valuation of a reinforcer (i.e., high drug demand) and excessive preference for immediate smaller rewards over larger delayed rewards (i.e., steeper delay discounting; (Bickel et al., 2014)).

Delay discounting refers to the reduction of the value of a reward with increasing delay to receiving it; immediate rewards are more highly valued than delayed ones. It is a useful index of impulsive decision-making, with steeper declines in delay discounting indicating the tendency to value immediate rewards over future rewards (MacKillop et al., 2010). Cannabis use has been associated with steeper delay discounting (Critchfield and Kollins, 2001), as has earlier age of onset of cannabis use (Heinz et al., 2013; Kollins, 2003). Thus, we expect individuals who use cannabis to have steeper delay discounting than those who do not. Given that delay discounting has been shown to predict cannabis use frequency and severity of CUD in adults (Aston et al., 2016; Strickland et al., 2017), it may be an important factor in understanding adolescents' higher risk for developing CUD. Indeed, in individuals receiving treatment for CUD, adolescents have been found to have steeper delay discounting than adults (Lee et al., 2015). Given steeper delay discounting in treatment-seeking adolescents who use cannabis (AdolescentsWUC), their ongoing development in impulse control and higher valuation of rewards (Shulman et al., 2016), we expect non-treatment seeking AdolescentsWUC to have steeper delay discounting than adults who use cannabis (AdultsWUC).

Relative reward valuation can be studied via hypothetical purchase tasks which measure drug demand (Zvorsky et al., 2019), such as the Marijuana Purchase Task (MPT; (Aston et al., 2015; Collins et al., 2014)). In this task, respondents indicate how many puffs of cannabis they would consume across escalating prices. Five indices can be obtained from the task: intensity (the amount of cannabis used at zero cost), $O_{\max}$ (total peak expenditure), $P_{\max}$ (price at peak expenditure), breakpoint (the cost at which cannabis demand is suppressed to zero) and elasticity (the degree to which cannabis use decreases with increasing price) (Bickel et al., 2014). These indices represent different aspects of demand and the motivation to obtain the drug (MacKillop and Kahler, 2009), and have been linked to different cannabis use outcomes (Aston and Meshesha, 2020). To the authors' knowledge, no study has yet compared cannabis demand in adolescents and adults using the MPT. However, given adolescents' putative higher valuation of rewards, greater risk of CUD, and incomplete maturation of executive functioning, we expect AdolescentsWUC to have greater cannabis demand on these indices, than AdultsWUC.

Our hypotheses, as registered on the Open Science Framework (OSF) (Borissova et al., 2021) were:

1a. Individuals who use cannabis will have steeper delay discounting than controls.

1b. There will be an interaction between age-group and use-of-cannabis-group on delay discounting, such that the difference between individuals who use cannabis and controls (where individuals who use cannabis > controls) will be greater for adolescents than for adults.

2. AdolescentsWUC will have greater cannabis demand across five indices for cannabis than AdultsWUC.

2. Methods

2.1. Study design

This is an analysis of cross-sectional data from the baseline session of the longitudinal CannTeen study (Lawn et al., 2022). The study protocol describes aims, participants, power analysis, data collection procedures, tasks and timelines (Lawn et al., 2020). The analysis plan for this study was registered before statistical analyses were conducted (Borissova et al., 2021).

Ethical approval was obtained from the University College London ethics committee, project ID 5929/003. The study was conducted in line with the Declaration of Helsinki, and all participants provided written and informed consent to participating.

2.2. Participants

The full sample comprised 274 participants (see Table 1 for a full breakdown by use-of-cannabis group and gender). Participants were recruited from the London area through school assemblies, posters, Facebook and Gumtree adverts.

Adolescents were aged between 16 and 17 years and adults were aged 26–29 years. Individuals who use cannabis reported using cannabis 1–7 days per week, on average, over the past three months. AdultsWUC were excluded if they had used cannabis on a weekly or more frequent basis before age 18.

Controls reported using either cannabis or tobacco at least once in their life but could not have used cannabis more than 10 times across their lifetime. Controls were excluded if they had used cannabis in the past month, or if they had used cannabis more than once in the past three months.

Exclusion criteria for all participants included (a) current daily use of psychotropic medication, (b) current treatment for any mental health (including cannabis use) disorder, (c) history of psychotic disorder, or (d) using any one illicit drug more than twice per month, averaged over the past three months, as self-reported at screening. See supplementary materials for the full list of inclusion/exclusion criteria.

2.3. Measures

2.3.1. Primary outcome variables

2.3.1.1. Delay discounting. Delay discounting was assessed using the Monetary Choice Questionnaire (MCQ) (Kirby et al., 1999). The MCQ consists of 27 hypothetical choices between receiving a specified amount of money today or a larger amount of money in the future. For example, "Would you prefer £ 55 today or £ 75 in 61 days?". The outcome variable for this task is the discounting rate (k), estimated for each participant from their choices, and represents how rapidly the value of future monetary rewards falls with time.

2.3.1.2. Cannabis demand. Cannabis demand was assessed using the modified MPT (Aston et al., 2015). This is a self-report questionnaire, comprising 22 hypothetical questions which asks the participant how many puffs of cannabis they would purchase at escalating prices. For example, "How many puffs of cannabis would you take if they were £X?". Participants were asked to respond according to a typical cannabis use day and as though the cannabis was of the typical quality they usually use (see supplementary materials for the full instructional vignette).

2.3.2. Pre-defined covariates

Maternal education was used as a proxy for socioeconomic status (SES) (Leadbeater et al., 2019), measured dichotomously as below undergraduate degree and undergraduate degree or above. Other illicit drug use was quantified dichotomously by at least monthly use of any illicit drug over the past three months, or less than this. Participants self-reported gender as male or female.

2.3.3. Other measures

A 12-week timeline follow-back (Robinson et al., 2014) was used to quantify frequency of cannabis, alcohol, tobacco, and other illicit drug use.

Cannabis Use Disorder Identification Test–Revised (CUDIT-R) was used as a continuous measure to assess symptoms of CUD. Higher scores reflect greater likelihood of CUD; thresholds for problematic use vary in the literature. Scores of ≥ 13 indicate a possible cannabis use disorder in adults (Adamson et al., 2010), though more recent studies comparing against DSM-5 criteria suggest a lower cut-off of ≥ 10 (Bonn-Miller et al., 2016). In younger samples, a lower cut-off score on the CUDIT-R may be more appropriate ($\geq$6 (Schultz et al., 2019), with a cut off of ≥ 9 having been used in non-clinical adolescent samples (Trangenstein et al., 2021).

Instant saliva drugs tests (Alere DDSV 703 or ALLTEST DSD-867MET/C) were administered to ensure that participants had not recently used cocaine, THC, opiates, amphetamine, methamphetamine, or benzodiazepines.

Blood alcohol concentration was measured using a breathalyser (Lion Alcometer 500) to ensure no alcohol had recently been consumed.

2.4. Procedure

Participants were first telephone-screened. Potentially eligible participants were then invited to a baseline session. At the start of the baseline session, inclusion and exclusion criteria and study-required abstinence (zero breathalyser reading, negative saliva drugs screen, self-reported alcohol and cannabis abstinence for 12 h, self-reported other illicit drug use abstinence for 48 h) were checked. Participants were excluded if study-required abstinence criteria were not met. We then collected the data for the measures described above. For full details of sessions, see the full protocol (Lawn et al., 2020).

2.5. Statistical analyses

2.5.1. Data pre-processing

Key details of pre-processing are described here, further details available in supplementary materials.

2.5.1.1. Delay discounting data. Missing data were imputed manually using the next closest option in the same response magnitude. This affected one item each for two participants. There were no other missing data. In total, seven participants were excluded for non-consistent responding as per guidelines in Gray et al., 2016. K was calculated using SPSS syntax provided by (Gray et al., 2016) and required log-transformation to normalise distributions.

2.5.1.2. MPT data. Only data for individuals who use cannabis were analysed. These were analysed by age-group for pre-processing. Data were examined for non-systematic responding based on standard criteria (Stein et al., 2015). No participants were excluded on this basis.

Raw MPT data were examined for outliers using standard scores, with a criterion of $Z = 3.29$. A small number of outliers were detected – 30/1672 data points (1.79%) in the adolescent data, 42/1562 data points (2.69%) in the adult data. These were recoded as one unit higher than the next lowest non-outlying value (Tabachnick and Fidell, 2000).

The five demand indices were calculated as per (Aston et al., 2015). Intensity, $O_{\max}$, $P_{\max}$ and breakpoint were observed directly from MPT performance. Elasticity was generated using a nonlinear exponential demand curve model (Koffarnus et al., 2015).

All demand indices were log-transformed to normalise distributions.

2.5.2. Data analysis

All data were analysed using IBM Statistical Package for Social Sciences (IBM SPSS version 26) and GraphPad Prism 9. After the transformations described above, all other statistical assumptions were met.

Participants with missing values on covariates (detailed in supplementary materials) were included in the ANOVA model but excluded from the ANCOVA model.

2.5.2.1. Delay discounting (Hypothesis 1a and b). We used a 2 × 2 factorial ANOVA model. The independent variables were age-group (adolescent vs. adult) and use-of-cannabis-group (individual with cannabis use vs. control). The dependent variable was the delay discounting rate (log k). The analysis was then conducted with pre-defined covariates of gender, SES and other drug use included as covariates in an ANCOVA model.

2.5.2.2. Cannabis demand (Hypothesis 2). Only data for individuals who use cannabis were analysed. Age-group was the single independent variable added to a univariate ANOVA to test each demand index as a dependent variable.

The analysis was then conducted with the pre-defined covariates in an ANCOVA model, again with each demand index as a dependent variable.

We applied an alpha threshold of 0.05. Significant interactions were analysed by conducting post hoc simple effects analysis, using Bonferroni-corrected tests, to unpack the direction of the interaction.

For non-significant results, we ran post hoc Bayesian t-tests to assess null findings for AdolescentsWUC vs. AdultsWUC, and adolescents vs. adults (combined individuals who use cannabis and controls), with no adjustment for covariates. We assumed equal variances and used a Jeffreys default prior. Bayes factors (BF_{01}) ≥ 3 support the null hypothesis of no difference.

2.5.2.3. Correlations. We ran bivariate correlations between all demand indices and cannabis use variables (frequency of use, CUDIT-R) to provide validation for the MPT indices in our sample. We applied a Bonferroni-correction with an alpha threshold of 0.006 to account for multiple correlations.

3. Results

3.1. Demographics (Table 1)

There were no significant differences between AdolescentsWUC (mean=3.73 ± 1.96 days/week) and AdultsWUC (mean=4.11 ± 1.88

Table 1
Summary of participant demographics. Sociodemographic and drug use variables for adolescent controls, adolescents who use cannabis (AdolescentsWUC), adult controls, and adults who use cannabis (AdultsWUC). Group differences are highlighted in the final column. *p < 0.05, **p < 0.01, ***p < 0.001. Dpw – days per week, dpm – days per month, CUDIT-R - Cannabis Use Disorder Identification Test – Revised. For continuous data mean (SD, min-max) is shown, for categorical data%(n) is shown.

	AdolescentsWUC (n = 76)	Adolescent control (n = 63)	AdultsWUC (n = 71)	Adult control (n = 64)	Group differences
Age (years)	17.10 (0.49, 16.26–18.00)	17.11 (0.47, 16.05–17.98)	27.63 (1.16, 26.00–29.92)	27.39 (1.01, 26.01–29.91)	Adult > adolescent ***
Gender – Female (%, n)	50% (38)	50.8% (32)	46.5% (33)	51.6% (33)	n.s.
Ethnicity (%, n)[a]					
White	68% (51)	63.5% (40)	63.4% (45)	64.1% (41)	
Mixed	20% (15)	11.1% (7)	11.3% (8)	4.7% (3)	
Asian	2.7% (2)	15.9% (10)	15.5% (11)	23.4% (15)	
Black	5.3% (4)	3.2% (2)	8.5% (6)	3.1% (2)	
Other	4% (3)	3.2% (2)	1.4% (1)	3.1% (2)	
Prefer not to say	0% (0)	3.2% (2)	0% (0)	1.6% (1)	
Cannabis use					
Age at first use[b]	14.61 (1.14, 11.00–16.58)	15.94 (0.80, 14.17–17.08)	18.00 (2.88, 13.00–25.00)	20.30 (3.24, 15.00–27.08)	Adult controls>AdultsWUC>Adolescent controlr>AdolescentsWUC ***
Cannabis use frequency (dpw)	3.73 (1.96, 0.83–6.92)	n/a	4.11 (1.88, 0.75–6.92)	n/a	n.s.
CUDIT-R[c]	15.38 (5.56, 5–27)	n/a	11.89 (4.84, 3–26)	n/a	AdolescentWUC > AdultsWUC***
Other drug use					
Alcohol use frequency (dpw)	0.63 (0.64, 0–3.25)	0.67 (0.75, 0–3.67)	1.47 (1.40, 0–6.83)	1.44 (1.05, 0–5.25)	Adult > adolescent ***
Alcohol use frequency (units/ week, Median (IQR))	2.73 (0.72–9.79)	2.20 (0.27–4.69)	4.93 (1.74–15.81)	5.05 (1.60–12.03)	AdultsWUC > Adolescent control *
Alcohol age at first use[d]	12.44 (5–17)	11.89 (5–17)	13.56 (5–21)	14.83 (7–27)	Adult control > AdolescentsWUC and adolescent control *** AdultsWUC> teen Control *
Amount cigarettes used (dpw)	2.84 (2.65, 0.08–7)	1.78 (2.53, 0.08–6.58)	2.38 (2.92, 0.08–7)	1.56 (2.29, 0.08–7)	n.s.
Any other illicit drug use - 1 dpm or greater (%, n)	59.2% (45)	3.2% (2)	25.4% (18)	1.6% (1)	Individuals who use cannabis>controls*** AdolescentsWUC>AdultsWUC***
Socioeconomic status					
Mother's education (undergraduate degree or above) (%, n)[e]	58.7% (44)	58.1% (36)	45.6% (31)	42.9% (27)	Adolescent>adult*

Notes:.
[a] N ethnicity= 75 AdolescentsWUC
[b] N age at first use = 70 AdultsWUC, 60 adult control, 55 adolescent control)
[c] one adult outlier, direction of results not changed so kept in.
[d] N at first use= 55 for adolescent control, 61 adult control
[e] N mother's education= 75 AdolescentsWUC, N = 62 adolescent control, N = 68 AdultsWUC, N = 63 adult control.

days/week) on cannabis use frequency (t_{145} =1.20, p = 0.23, d=0.20). AdolescentsWUC (mean=17.10 ± 0.49 years) and adolescent controls (mean=17.11 ± 0.47 years) did not differ significantly in age (t_{137} =0.22, p = 0.82, d=0.04); AdultsWUC (mean=27.63 ± 1.16 years) and adult controls (mean=27.39 years ± 1.01) also did not differ significantly in age (t_{145}=1.23, p = 0.22, d=0.21).

CUDIT-R score was higher in AdolescentsWUC (mean=15.38 ± 5.56) than for AdultsWUC (mean= 11.89 ± 4.84) (t_{146} =30.24, p < 0.001, d=0.67). Adults (mean=1.45 ± 1.24 days/week) consumed alcohol on more days than adolescents (mean=0.65 ± 0.69 days/week) ($F_{1,270}$ =44.11, $p < 0.001$, η_p^2=0.14). Individuals who use cannabis were more likely to use other illicit drugs on a monthly basis than controls (χ_1^2 =61.10, $p < 0.001$). Additionally, AdolescentsWUC were more likely to use other illicit drugs on a monthly basis than AdultsWUC (χ_1^2 =17.18, p < 0.001). Groups did not significantly differ on cigarette consumption. Adolescents had a significantly higher SES than adults (χ_1^2 =5.345, p = 0.021).

3.2. Delay discounting

Descriptive statistics of non-transformed k are in Table 2. Descriptive statistics of log-transformed k are in supplementary Table S2.

There was a main effect of use-of-cannabis group, with individuals who use cannabis having steeper delay discounting than controls (F, (1,263)= 14.29, p < 0.001, η_p^2= 0.05). This effect persisted after adjusting for covariates (F, (1,254)= 9.13, p = 0.003, η_p^2= 0.04).

There was no significant interaction (F, (1,263)= 1.645, p = 0.20 η_p^2= 0.01) or main effect of age group (F, (1, 263)= 2.64, p = 0.11, η_p^2= 0.01). After adjusting for covariates, there remained no significant interaction (F, (1,254)= 1.07, p = 0.30, η_p^2= 0.004) or main effect of age group (F,(1,254)= 3.80, p = 0.053, η_p^2= 0.02). Bayesian analyses supported the null hypothesis that AdultsWUC and AdolescentsWUC had similar delay discounting (BF_{01} =7.51). However, Bayesian analyses did not support the null hypothesis that adults and adolescents had similar delay discounting (BF_{01} =2.95).

Table 2
Descriptive statistics for the outcome variable (mean k) from the delay discounting task. The non-transformed values are shown. The log-transformed and adjusted for covariates k are listed in the supplementary materials. Mean (SD), minimum-maximum are shown.

	AdolescentsWUC		Adolescent control		AdultsWUC		Adult control	
	Mean (SD)	Min-Max	Mean (SD)	Min-Max	Mean (SD)	Min-Max	Mean (SD)	Min-Max
k	0.02 (0.02)	0.0003–0.14	0.01 (0.01)	0.0002–0.047	0.14 (0.01)	0.0006–0.09	0.008 (0.01)	0.0003–0.06

3.3. Marijuana demand

Descriptive statistics of non-transformed indices are in Table 3. Descriptive statistics of log-transformed indices are included in supplementary Table S3.

Intensity was higher in AdolescentsWUC than AdultsWUC (F, (1,145)= 12.06, $p = 0.001$, η_p^2= 0.08), which remained significant after adjusting for covariates (F, (1,138)= 9.76, $p = 0.002$, η_p^2= 0.07).

AdolescentsWUC had significantly lower elasticity (F, (1,145)= 12.67, $p = 0.001$, η_p^2= 0.08) than AdultsWUC, which persisted after adjusting for covariates (F, (1,138)= 15.25, $p < 0.001$, η_p^2= 0.10).

AdultsWUC had higher P_{max} (F, (1,145)= 4.60, $p = 0.03$, η_p^2= 0.03) than AdolescentsWUC, however this did not remain significant after adjusting for covariates (F, (1,138)= 1.77, $p = 0.19$, η_p^2= 0.01).

There was no significant difference between AdultsWUC and AdolescentsWUC on O_{max} in the unadjusted (F, (1,145)= 0.07, $p = 0.80$, η_p^2= 0.00) or adjusted analysis (F, (1,138)= 0.10, $p = 0.75$, η_p^2= 0.001). Bayesian analyses supported the null hypothesis that AdultsWUC and AdolescentsWUC had similar O_{max} ($BF_{01} = 7.54$).

There was also no significant difference between age groups on breakpoint when unadjusted (F, (1,145)= 0.98, $p = 0.32$, η_p^2= 0.01) or after adjusting for covariates (F, (1,138)= 0.07, $p = 0.79$, η_p^2= 0.001). Bayesian analyses supported the null hypothesis that AdultsWUC and AdolescentsWUC had similar breakpoint ($BF_{01} = 4.88$).

Fig. 1 demonstrates mean consumption and mean expenditure in AdultsWUC and AdolescentsWUC.

3.4. Correlations (Table 4)

In both adolescents (Fig. 2a) and adults (Fig. 3a), intensity was significantly positively correlated with cannabis use frequency. In adolescents only, intensity (Fig. 2b) and P_{max} were significantly positively correlated with CUDIT-R.

There were no significant correlations between covariates and outcome variables (Table S4).

4. Discussion

This study investigated delay discounting of monetary rewards and cannabis demand in AdultsWUC and AdolescentsWUC, and controls. Individuals who use cannabis had steeper discounting than controls. There was no difference between adolescents and adults on delay discounting, nor an interaction between age-group and use-of-cannabis-group. There was also Bayesian support for AdultsWUC and AdolescentsWUC having similar delay discounting. With respect to cannabis demand, AdolescentsWUC showed lower elasticity, i.e., less sensitivity to price, and higher intensity, i.e., greater consumption at zero price. There was no difference between AdultsWUC and AdolescentsWUC on P_{max}, $O_{max,}$ and breakpoint, after adjusting for covariates. Exploratory analyses suggested that the MPT is associated with adolescent cannabis use outcomes, with intensity correlating with both cannabis use frequency and problematic use,.

Table 3
Descriptive statistics for the outcome variables from the MPT. The non-transformed demand indices for AdultsWUC and AdolescentsWUC are shown. These are based on the pre-processed and winsorized data. The log-transformed and adjusted for covariates indices are listed in the supplementary materials. Mean (SD), minimum-maximum are shown.

Demand metric	Adult		Adolescent	
	Mean (SD)	Min-Max	Mean (SD)	Min-Max
O_{max}	20.37 (41.74)	1–220	10.81 (11.04)	0.5–56
P_{max}	3.46 (5.76)	0.1–20	1.37 (2.36)	0.05–20
Intensity	22.64 (21.75)	3–91	44.43 (47.61)	3–201
Breakpoint	5.11 (6.50)	0.2–20	3.11 (3.76)	0.3–20
Elasticity	0.04 (0.04)	0.000692–0.21	0.02 (0.02)	0.001–0.16

The association between steeper discounting and cannabis use aligns with previous studies (Aston et al., 2016; Heinz et al., 2013; Lopez-Vergara et al., 2019; O'Donnell et al., 2021), although null effects have also been found (Jarmolowicz et al., 2020; Strickland et al., 2017). It has been shown that delay discounting is a stable trait characteristic, independent of environmental factors (De Wilde et al., 2013; Kirby, 2009), that predates drug use (Verdejo-García et al., 2008). Thus, steeper delay discounting may be a risk factor for cannabis use initiation. The current consensus suggests that cannabis use does not itself increase preferences for immediate rewards (Poulton and Hester, 2020), though some animal studies have demonstrated this with other drugs (Setlow et al., 2009). However, delay discounting can become more shallow over the course of substance abuse treatment (Black and Rosen, 2011; Landes et al., 2012), suggesting that changes in substance use may modify discounting rates. Longitudinal studies are warranted to examine how time-varying cannabis use impacts upon delay discounting.

We found no significant difference between AdultsWUC and AdolescentsWUC on delay discounting rates, and this was supported by a Bayesian analysis. Previous research has shown associations between earlier age of onset with steeper delay discounting (Heinz et al., 2013; Kollins, 2003) and significant differences between AdultsWUC and AdolescentsWUC in treatment for CUD (Lee et al., 2015). Given that our delay discounting task detected an effect between individuals who use cannabis and controls, the null age effect is unlikely due to the insensitivity of the measure used. Our findings are consistent with previous work, in which the heightened vulnerability of cannabis use in adolescence has been equivocal (Crane et al., 2013; Scott et al., 2017). Scott et al. (2017) found that the relationship between heavy cannabis use and cognition in adult and adolescents was not moderated by age-group or age of initiation. Age effects previously found may simply reflect changes in delay discounting that occur over time (Green et al., 1994; Steinberg et al., 2009; Yu et al., 2021), rather than the heightened impact of cannabis exposure. Furthermore, the magnitude of cognitive deficits associated with cannabis use in youth may have been previously overstated (Scott et al., 2018); positive findings may have reflected residual effects from acute use or withdrawal (Grant et al., 2003; Schreiner and Dunn, 2012), or reflected uncontrolled confounders (National Academies of Sciences, Engineering, and Medicine et al., 2017; Scott et al., 2018). The dearth of null findings in this area may also be underreported due to publication bias (Franco et al., 2014; Ioannidis, 2005).

Intensity was higher in AdolescentsWUC (i.e., they purchased more cannabis at zero cost). This may be due to neurobiological differences impacting on impulsivity and reduced appreciation for consequences (Ernst et al., 2006; Galvan et al., 2006), as well as higher sensitivity to rewards (Forbes et al., 2010). Psycho-social factors including peer influences (Chein et al., 2011), risk-taking and sensation seeking traits (Glicksohn et al., 2018; Steinberg et al., 2008), fewer next-day responsibilities (Ferguson et al., 2021) and perceived health risks of cannabis (Järvinen and Demant, 2011), may also contribute to adolescents seeking higher levels of intoxication than adults. Furthermore, one study demonstrated adolescents to have less cannabis satiety and lower intoxication effects after acute administration of cannabis compared to adults (Mokrysz et al., 2016), though in an older sample of infrequent AdolescentsWUC did not differ in subjective effects (Murray et al., 2022). This suggests adolescents may consume more cannabis in a smoking session than adults, related to generally higher demand, which may put them at greater risk for adverse outcomes (Kroon et al., 2020).

Adolescents' lower elasticity of demand reflects greater insensitivity to increases in cannabis price than adults. While this supports our hypothesis of higher cannabis demand in adolescents overall, these findings are surprising given that they are likely to have less money than adults. Studies have shown that cannabis use initiation in adolescents is sensitive to price changes (Pacula and Lundberg, 2014; van Ours and Williams, 2007). However, these studies took place in different

Table 4
Correlations for AdultsWUC and AdolescentsWUC between log-demand indices, log k (delay discounting outcome), cannabis use frequency (days per week-dpw), and cannabis use disorder identification test- revised (CUDIT-R) score. Significant correlations are highlighted in bold. Pearson r correlations are shown. **p < 0.006, ***p < 0.001. Abbreviations: Adol – adolescent. Cannabis use freq – cannabis use frequency. CUDIT-R – Cannabis Use Disorder Identification Test– Revised.

	logO_{max}		logP_{max}		logIntensity		logBreakpoint		logElasticity		Cannabis use freq		CUDIT-R		log k	
	Adol	Adult	Adol	Adult	Adol	Adult	Adol	Adult	Adol	Adult	Adol	Adult	Adol	Adult	Adol	Adult
logO_{max}			**0.48** ***	**0.71** ***	**0.47** ***	**0.47** ***	**0.56** ***	**0.76** ***	**-0.93** ***	**-0.96** ***	0.26	0.15	0.09	0.15	0.07	0.26
logP_{max}	**0.48** ***	**0.71** ***			-0.21	-0.02	**0.80** ***	**0.93** ***	**-0.36** **	-0.65	-0.15	0.05	**-0.34** **	0.06	-0.10	0.25
logIntensity	**0.47** ***	**0.47** ***	-0.21	-0.02			-0.08	0.07	**-0.40** ***	**-0.47** ***	**0.51** ***	**0.36** **	**0.41** ***	0.27	0.13	0.12
logBreakpoint	**0.56** ***	**0.76** ***	**0.80** ***	**0.93** ***	-0.08	0.07			**-0.49** ***	**-0.72** ***	0.12	0.02	-0.10	0.10	-0.08	0.24
logElasticity	**-0.93** ***	**-0.96** ***	**-0.36** **	-0.65	**-0.40** ***	**-0.47** ***	**-0.49** ***	**-0.72** ***			-0.23	-0.18	-0.11	-0.12	-0.10	-0.25
Cannabis use freq	0.26	0.15	-0.15	0.05	**0.51** ***	**0.36** **	0.12	0.02	-0.23	-0.18			**0.63** ***	**0.45** ***	0.11	0.05
CUDIT-R	0.09	0.15	**- 0.34** **	0.06	**-0.41** ***	0.27	-0.10	0.10	-0.11	-0.12	**0.63** ***	**0.45** ***			0.17	0.11
log k	0.07	0.26	-0.10	0.25	0.13	0.12	-0.08	0.24	-0.10	-0.25	0.11	0.05	0.17	0.11		

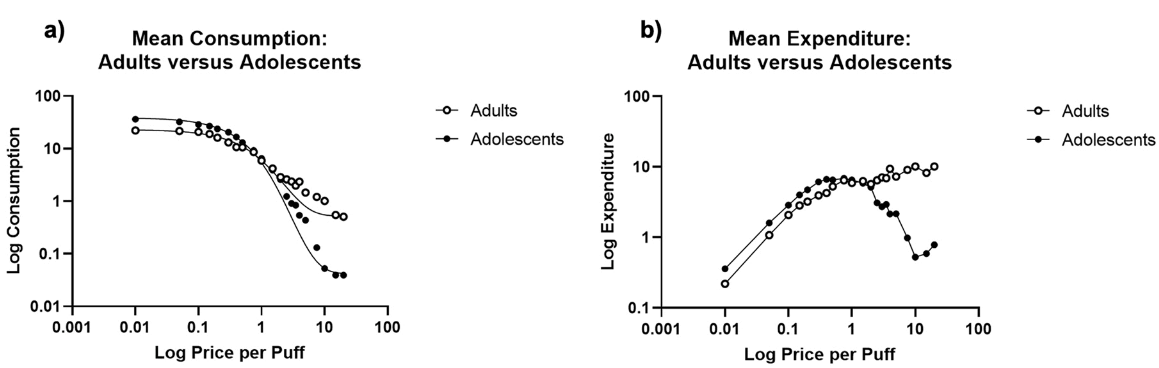

Fig. 1. a) Demand curve for consumption of cannabis puffs. The x-axis provides log-transformed price in pounds and the y-axis provides log-transformed self-reported consumption in cannabis puffs. b) Expenditure curve for cannabis puffs. The x-axis provides log-transformed price in pounds and the y-axis provides log-transformed expenditure in pounds.

socio-cultural, economic, and legal contexts which may interact with price to influence elasticity. Adults' sensitivity to price may reflect their greater purchasing experience. This is especially useful when assessing the value of "puffs" in the MPT, which depart from usual purchasing behaviour. Adults may also have greater understanding of how money must be allocated across different responsibilities. These findings indicate that adolescents are willing to buy more cannabis than adults both when it is free, but also at ever-increasing costs, contributing to their overall more problematic use, as evidenced herein via elevated CUDIT scores. Thus, increasing cannabis pricing may be insufficient in deterring adolescent cannabis consumption.

The two aspects of a Reinforcer Pathology approach to understanding problematic cannabis use, steep delay discounting and high demand, were demonstrated in AdultsWUC and AdolescentsWUC. Steeper discounting in individuals who use cannabis has been linked to measures of problematic cannabis use, including craving and dependence symptoms (Aston et al., 2016; Heinz et al., 2013; Kollins, 2003; Strickland et al., 2017). However, our study did not find a correlation between delay discounting and cannabis use frequency or CUDIT-R scores in adults or adolescents. Future studies may wish to include a delay discounting task that includes cannabis, as outcomes from cannabis delay discounting tasks have been associated with both cannabis use frequency and cannabis dependence symptoms (Strickland et al., 2017; Strickland et al., 2020) and may be related to treatment outcomes for CUD in adolescents (Stanger et al., 2012).

Both lower elasticity and higher intensity shown in AdolescentsWUC in our study have, in adults, been linked to greater quantity of use (Minhas et al., 2021; Strickland et al., 2019), craving, and dependence symptoms (Aston et al., 2015). This is further validated in the present study with correlations between intensity and cannabis use frequency in

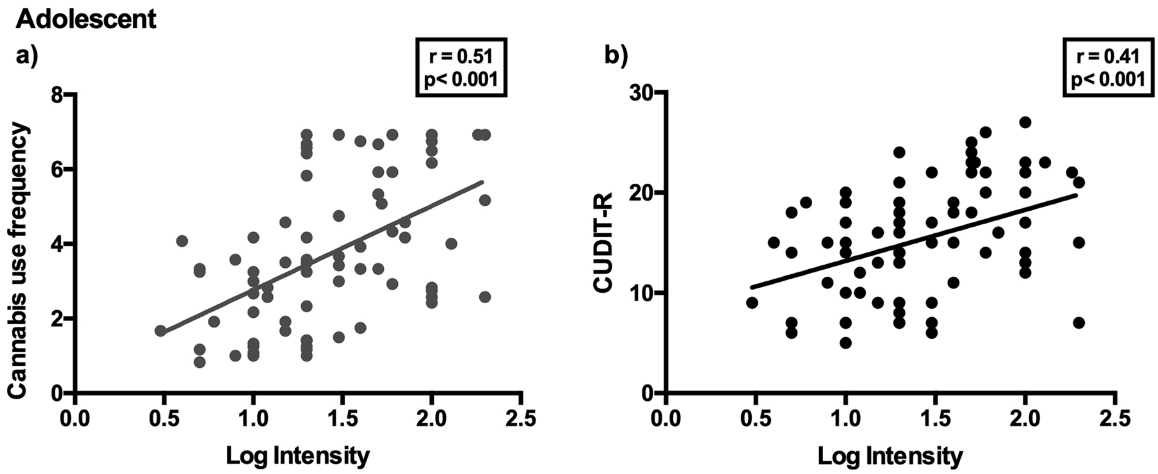

Fig. 2. a) Scatter plot to show significant positive correlation between adolescent logIntensity and cannabis use frequency (days/week), $r = 0.51$, $p < 0.001$. b) Scatter plot to show correlation between adolescent logIntensity and CUDIT-R score, $r = 0.41$, $p < 0.001$.

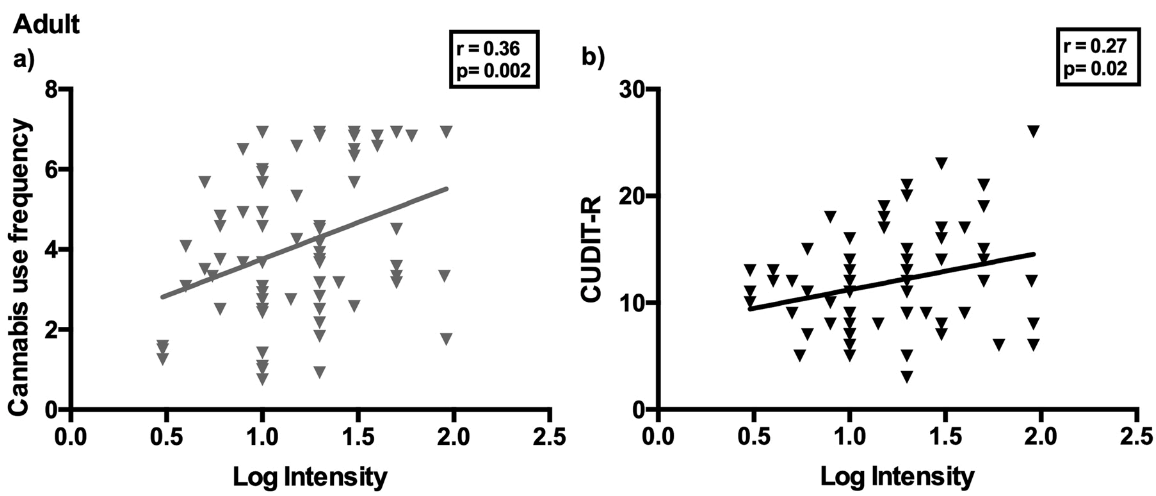

Fig. 3. a) Scatter plot to show significant positive correlation between adult logIntensity and cannabis use frequency (days/week), $r = 0.36$, $p = 0.002$. b) Scatter plot to show non-significant positive correlation between adult logIntensity and CUDIT-R score, $r = 0.27$, $p = 0.02$.

both AdultsWUC and AdolescentsWUC, well as CUDIT-R scores in AdolescentsWUC. Thus, AdolescentsWUC exhibit aspects of Reinforcer Pathology that may underlie their more serious cannabis use and contribute to their greater vulnerability to CUD (Winters and Lee, 2008). These findings may aid in developing policy or treatment targeting specific aspects of decision-making underpinning problematic cannabis use. However, the relationship between the Marijuana Purchase Task indices and cannabis use frequency/problematic use were not one of our pre-registered hypotheses, so any interpretation must be cautious.

Interestingly, a separate analysis of cross-sectional 'CannTeen' data has found AdolescentsWUC to have greater odds of having severe CUD than AdultsWUC, measured by DSM-5 symptoms (Lawn et al., 2022). Our findings of age-differences in cannabis demand suggest that adolescents may be in a riskier category who are less sensitive to price and have greater cannabis consumption when it is free. This may be one factor that increases their vulnerability to problematic cannabis use. This may combine with the finding that overall individuals who use cannabis had steeper delay discounting than controls.

Insight from these behavioural economic measures may be important for public policy concerning cannabis unit pricing and the age at which cannabis can be legally consumed in parts of the world where it is licit. Future studies should examine the relationship between aspects of Reinforcer Pathology in adolescent and AdultsWUC longitudinally and examine associations with cannabis use severity. Including cannabis-using adolescents of a younger age, and adolescents in treatment for CUD, may help to further illuminate the role of Reinforcer Pathology in their cannabis use.

4.1. Strengths & limitations

To our knowledge, this was the first study to compare non-treatment seeking cannabis using adolescents with adults on measures of delay discounting and cannabis demand. Our study benefited from directly comparing current cannabis use in adolescents with adults, rather than in adults with different ages of onset. Furthermore, AdultsWUC and AdolescentsWUC were well-matched on frequency of cannabis use. It is worth noting that adolescents had used drugs other than cannabis at a younger age than the adults. However, this would be expected given the adults' higher age. Importantly, our participants had low levels of alcohol and other drug use and recent drug use was similar between AdultsWUC and AdolescentsWUC. Controls were closely matched on age and gender. They had some cannabis or tobacco exposure, reducing unmeasured confounders. We objectively assessed abstinence from drugs, controlled for pre-defined covariates, and pre-registered analyses plans. Our sample size was also large relative to previous studies. However, findings should be viewed in the context of the following limitations. We targeted individuals who used cannabis regularly, who may be non-representative of individuals who use cannabis in the wider population. Furthermore, socio-cultural factors limit whether our findings can be extrapolated to other parts of the world. The age-groups selected were highly specific in order to compare matched groups of adolescents and adults with greatest precision, but they may not generalize to other age groups that were not included in our design, for instance younger adolescents. Lastly, it would be beneficial to study if there is a longitudinal impact of the age differences we found on future cannabis use.

5. Conclusions

Overall, individuals who use cannabis had steeper delay discounting than controls. AdolescentsWUC were less sensitive than AdultsWUC to increasing price and 'used' more cannabis at zero cost, variables which are each associated with problem use. These behavioural economic findings should be considered in future research into the aetiology of adolescent CUD.

Role of funding source

This work was supported by a grant from the Medical Research Council (MRC; award number MR/P012728/1) to HVC and TPF. AB is supported by a fellowship from the National Institute for Health Research (NIHR) UCLH Biomedical Research Centre and a NIHR Academic Clinical Fellowship. HVC is supported by grants from the MRC, United Kingdom (UK) Department of Health and by the National Institute for Health Research UCLH Biomedical Research Centre. MBW's primary employer is Invicro LLC, a contract research organisation which performs commercial research for the pharmaceutical and biotechnology industries. MAPB is supported by grants from UK Research and Innovation, University College London, the British Medical Association Foundation for Medical Research, and the National Institute for Health University College London Hospitals Biomedical Research Centre. ERA is funded by NIGMS (National Institute of General Medical Sciences) COBRE grant P20GM130414.

The funding source did not have any direct role in the study design, data collection and analysis, report writing, or manuscript submission.

CRediT authorship contribution statement

HVC was principal investigator on the CannTeen study. HVC, CM, TF, WL, MW, MAPB contributed to the conception and design of the study. AB, SS, CM, WL, RL, KP, EM, AP contributed to data collection. AB, SS, ERA analysed the data, with critical input from WL and CM. AB and SS drafted the manuscript with critical revision from ERA and WL. MAPB provided medical oversight to the study. All authors contributed edits to the text and have approved the final manuscript.

Acknowledgments

We would like to thank all of the CannTeen participants for so generously giving up their time to take part. We would also like to thank everyone who contributed to data collection, Invicro staff, and Sharinjeet Dhiman.

Conflict of Interest

No authors have any relevant conflicts of interest to disclose.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.drugalcdep.2022.109531.

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