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Can delay discounting predict vaccine hesitancy 4-years later? A study among US young adults

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ABSTRACT

Despite being a major threat to health, vaccine hesitancy (i.e., refusal or reluctance to vaccinate despite vaccine availability) is on the rise. Using a longitudinal cohort of young adults (N = 1260) from Los Angeles County, California we investigated the neurobehavioral mechanisms underlying COVID-19 vaccine hesitancy. Data were collected at two time points: during adolescence (12th grade; fall 2016; average age = 16.96 (±0.42)) and during young adulthood (spring 2021; average age = 21.33 (±0.49)). Main outcomes and measures were delay discounting (DD; fall 2016) and tendency to act rashly when experiencing positive and negative emotions (UPPS-P; fall 2016); self-reported vaccine hesitancy and vaccine beliefs/knowledge (spring 2021). A principal components analysis determined four COVID-19 vaccine beliefs/knowledge themes: *Collective Responsibility, Confidence and Risk Calculation, Complacency,* and *Convenience*. Significant relationships were found between themes, COVID-19 vaccine hesitancy, and DD. *Collective Responsibility* (β = -1.158[-1.213,-1.102]) and *Convenience* (β = -0.132 [-0.185,-0.078]) scores were negatively associated, while *Confidence and Risk Calculation* (β = 0.283 [0.230,0.337]) and *Complacency* (β = 0.412[0.358,0.466]) scores were positively associated with COVID-19 vaccine hesitancy. Additionally, *Collective Responsibility* (β = -0.060[-0.101,-0.018]) was negatively associated, and *Complacency* (β = -0.063[0.021,0.105]) was positively associated with DD from fall 2016. Mediation analysis revealed immediacy bias during adolescence, measured by DD, predicted vaccine hesitancy 4 years later while being mediated by two types of vaccine beliefs/knowledge: *Collective Responsibility* (β = 0.069[0.022,0.116]) and *Complacency* (β = 0.026[0.008,0.044]). These findings provide a further understanding of individual vaccine-related decision-making among young adults and inform public health messaging to increase vaccination acceptance.

"We're not just fighting an epidemic; we're fighting an infodemic"

(WHO TEAM Epidemic and Pandemic Preparedness and Prevention (EPP), 2020)

Vaccine hesitancy (i.e., refusal or reluctance to vaccinate despite the availability of vaccines) is on the rise, listed by the World Health Organization (WHO) as a major threat to health (WHO, 2019). In the United States (US), vaccine hesitancy has contributed to increases in the prevalence of vaccine-preventable diseases (VPDs; Aloe et al., 2017; CDC, 2022a,b; Patel et al., 2019; Phadke et al., 2016), especially for VPDs that require ongoing adolescent and adult vaccinations (Hinman and Orenstein, 2007). For example, the vaccine uptake for tetanus, diphtheria, and pertussis (Tdap) amongst adolescents is 88.9% (Roper et al., 2021). Whereas vaccine uptake in the 2020–2021 influenza season was around 50% (CDC, 2021a). Finally, despite COVID-19 vaccines being widely available across the US since July 2021, only 69.4% of the US population completed the primary series and only 16.8% received the updated bivalent booster (CDC, n.d.) as of April 2023.

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Understanding vaccine hesitancy, especially regular vaccinations, is an ongoing public health problem.

Many studies in high-income nations have examined a variety of sociodemographic variables such as race and ethnicity (CDC, 2022c; Dai et al., 2022; Gerretsen et al., 2021; Liu and Li, 2021; National Center for Health Statistics, 2019; Savoia et al., 2021), geographical regions (National Center for Health Statistics, 2019), sex (Gerretsen et al., 2021; Liu and Li, 2021; McElfish et al., 2021), age (Gerretsen et al., 2021; McElfish et al., 2021), education (McElfish et al. 2021), political affiliation (Gerretsen et al., 2021; Liu and Li, 2021), and employment (Gerretsen et al., 2021) that are related to vaccine hesitancy. While these studies may identify who should be targeted with additional efforts and resources, "they cannot be used to explain the emergence or intensity [of vaccine hesitancy]. Most importantly, without looking at psychological factors, they may be useless to inform interventions to counter hesitancy" (WHO, 2016, pp. 14–15). In support of this, a 2016 systematic review of influenza vaccine hesitancy found that psychological determinants that explain the emergence of vaccine hesitancy (i.e., why) were more meaningfully related to vaccine uptake (Schmid et al., 2017).

Research aimed at elucidating why vaccine hesitancy exists has suggested two distinct levels of influence: meso and micro. The *meso*-level seeks to identify social, contextual, and vaccine-specific factors that externally influence health-related decision-making (Schmid et al., 2017). Together, models examining *meso*-level influences of vaccine hesitancy have delineated five commonly found factors, including: complacency, confidence, convenience (Betsch et al., 2018; Larson et al., 2014; MacDonald and SAGE Working Group on Vaccine Hesitancy, 2015; WHO, 2016; Wiysonge et al., 2022), calculation of risk (Betsch et al., 2018, 2015; WHO, 2016; Wiysonge et al., 2022), and collective responsibility (Betsch et al., 2018; Wiysonge et al., 2022). Complacency comprises beliefs that risks of infection are low (Betsch et al., 2018). Convenience (or, constraints) captures access barriers (e.g., availability or affordability) limiting vaccination (Betsch et al., 2018). Risk calculation refers to an individual's information gathering that may facilitate or hinder vaccination (Betsch et al., 2018). Confidence includes trust in healthcare workers, scientists, and policymakers (Betsch et al., 2018). Finally, collective responsibility is a belief in the need to protect the community (Betsch et al., 2018). The 5C's have been found for different vaccines, including influenza (Schmid et al., 2017) and COVID (Schmid et al., 2017). Recent research on COVID-19 vaccine hesitancy has cited: perceptions of decreased efficacy of infection prevention (Kreps et al., 2020; Shih et al., 2021) decreased protection duration (Kreps et al., 2020), medical mistrust or adverse effects/safety concerns (Aw et al., 2021; Kreps et al., 2020), lesser perceived risk of contracting and/or having a severe case (Aw et al., 2021; Kreps et al., 2020; Shih et al., 2021), FDA emergency use authorization (i.e., rapid development; Aw et al., 2021; Kreps et al., 2020), and misinformation (Roozenbeek et al., 2020).

On the micro-level, the research seeks to elucidate how health-related decision-making and behavior is mechanistically explained via neuropsychological processes (Schmid et al., 2017). In this context, we sought to extend the literature on the relationship between other constructs of health related decision-making, specifically neuroeconomics, and vaccine hesitancy. Neuroeconomics is a field that integrates psychology, neuroscience, and economics to understand the neural substrates of decision-making (Bickel et al., 2011a). The competing neurobehavioral decision systems (CNDS) theory (Amlung et al., 2019; Koffarnus et al., 2013; McClure et al., 2004) is a dual-decision systems model developed within neuroeconomics that explains patterns of decision-making. According to CNDS theory, suboptimal choices that consider immediate benefits are driven predominantly by the impulsive system, which is associated with the salience and valuation of immediate rewards (i.e., an immediacy bias). Conversely, ideal choices that fully consider the immediate and longer-term potential outcomes are associated with the executive system, which is associated with cognitive functions such as planning, memory, and inhibition (Jarmolowicz et al., 2016). Together, decision-making is influenced by the interaction between the executive and impulsive neural systems (McClure et al., 2004; McClure and Bickel, 2014), deemed to be stable over time (Kirby, 2009; MacKillop, 2013). A regulatory imbalance between the two systems can result in poor health behaviors (Bickel et al., 2016, 2014b, 2012; Story et al., 2014). Delay discounting indexes CNDS balance (Bickel et al., 2012) which is further supported by neuroimaging studies (Bickel et al., 2009; Hoffman et al., 2008; Kable and Glimcher, 2007; McClure et al., 2007, 2004; Meade et al., 2011; Monterosso et al., 2007).

Delay discounting describes the subjective devaluation of a reward when it is delayed (Madden and Bickel, 2010; Mazur, 1987; Odum, 2011; Rachlin et al., 1991). Delay discounting tasks typically have individuals decide between a smaller, immediate commodity (e.g., $100 today) and a larger, delayed commodity (e.g., $1000 in one week). Consistent with CNDS theory, higher delay discounting is related to a variety of health conditions and maladaptive behaviors (Story et al., 2014), including substance use (Bickel et al., 2014c), obesity (Davis et al., 2010; Fields et al., 2011; Kulendran et al., 2013; Weller et al., 2008), not wearing seat belts (Daugherty and Brase, 2010), needle-sharing in heroin users (Odum et al., 2000),Chesson et al., 2006). Related to COVID-19 specifically, higher delay discounting rates were associated with decreased adherence to social distancing (Lloyd et al., 2021) and found amongst unvaccinated individuals in a representative Canadian sample (Hudson et al., 2022) and across a multinational sample recruited from 13 countries (Halilova et al., 2022). Despite the robustness of delay discounting in predicting poor health-related decisions and recent evidence that discounting can explain COVID-19 protective behaviors, neurobehavioral mechanisms underpinning vaccine hesitancy amongst young adults have yet to be examined.

One mechanism by which delay discounting (i.e. a micro-level construct) could contribute to vaccine hesitancy is by increasing the propensity toward developing knowledge and beliefs about vaccines (i.e. a *meso*-level influence) that discourages vaccine uptake. Further, individual differences in decision-making processes underpinned by neurobehavioral phenotypes originating in adolescence might also explain young adult vaccine hesitancy. This study examined the relationship between vaccine beliefs and knowledge and delay discounting in predicting vaccine hesitancy. To this end, we analyzed a longitudinal cohort study among young adults from Los Angeles (LA) County, California, to examine if delay discounting during adolescence predicted future (approximately four years later) COVID-19 vaccine hesitancy during young adulthood. We employed a data-driven approach to identify vaccine beliefs/knowledge themes. Lastly, we evaluated whether the relationship between delay discounting and COVID-19 vaccine hesitancy was mediated by vaccine beliefs/knowledge.

1. Methods

1.1. Participants and procedure

Data were retrieved from the Happiness & Health Study, a prospective cohort survey of behavioral health aimed at understanding trends across the lifespan, which enrolled 3,396 students in 9th grade from ten schools in LA County in 2013 (see eTable 1 for school characteristics). Paper-and-pencil follow-up surveys occurred semi-annually in the classroom and online follow-up surveys continued after 2017. Participants provided assent and parental consent to be surveyed and were reconsented as adults. The University of Southern California Institutional Review Board approved the study.

Measures analyzed in the current study were collected at two-time points: in fall 2016 (12th grade; baseline) and spring 2021 during Jan-May when COVID-19 vaccine availability rapidly rose (follow-up; see *Measures* for details). The sample included 1260 participants who completed all measures at both time points (eFigure 1). Note individuals in this cohort had not yet received the COVID-19 vaccine. Participants were not included in the analysis if they did not complete the delay discounting measure (those unavailable to complete the baseline assessment and provided an abbreviated survey) or the vaccine beliefs/knowledge questions (those who had received a COVID-19 vaccine).

1.2. Measures

Demographic, decision-making, and COVID-related measures were collected.

1.2.1. Demographics

Participants' characteristics, including sex, age, race/ethnicity, in a degree program, and employment were collected using self-report with predefined categories. Race/ethnicity were collected in fall 2016 and all other demographic characteristics were obtained in spring 2021 (the most current data collection). Employment was aggregated into three levels: working (Work full-time at least 35 h per week/Work part-time 15–34 h per week/Work part-time<15 h per week), not-working (I don't currently work for pay), and other (Don't know/Prefer not to say).

1.2.2. Delay discounting

Delay discounting was assessed in fall of 2016 using the 21-item Monetary Choice Questionnaire (MCQ; Kirby and Maraković, 1996). The MCQ was scored as described in Kaplan et al. (2016) and quantified using ln(k), with a higher score reflecting a greater rate of delay discounting. The MCQ was included as our primary index of decision-making (see Supplement for details).

1.2.3. Urgency, Premeditation (lack of), Perseverance (lack of), Sensation Seeking, Positive Urgency, Impulsive Behavior Scale (UPPS-P) subscales

Emotional reactivity to negative and positive experiences was assessed in the fall of 2016 using the positive and negative urgency subscales of the *UPPS* (Cyders et al., 2007; Whiteside and Lynam, 2001). Higher scores on the Negative and Positive Urgency subscales reflect a more emotion-based rash action. Weighted sum scores were generated for each subscale by averaging across observed values and multiplying by the total number of questions. An Urgency composite to reflect emotional reactivity was created using the sum of the two subscales ranging from 26 to 104. The UPPS-P Negative and Positive Urgency Subscales were included as an alternative index of decision-making.

1.2.4. COVID-19 vaccine beliefs/knowledge

Participants were asked to rate how much they agreed or disagreed with 19 statements regarding the COVID-19 vaccine (see Box 1 for items). These statements were rated on a five-point Likert scale (1 = 'Strongly Disagree' to 5 = 'Strongly Agree').

Beliefs/knowledge theme scores. Principal components analysis (PCA), a dimension reduction technique, was used to identify a set of principal components (PCs) that explain the most variability in the 19 COVID-19 vaccine beliefs/knowledge questions. PCA was implemented using an oblique transformation to allow for correlations among PCs. The number of PCs (i.e., "belief/knowledge themes") was identified by using Kaiser's criterion (eigenvalues greater than one; Field et al., 2012) due to the limited number of variables and large sample size (Stevens, 2002) while also ensuring interpretability. The Kaiser-Meyer-Olkin measure (KMO) score of 0.91 verified the sampling adequacy of the analysis ('marvelous' according to Kaiser 1974), and all KMO values for the individual 19 items were > 0.65, which is above the acceptable limit of 0.5. The Bartlett's test of sphericity, $X2(171) = 17{,}101.35$, $p < 0.001$, indicated that the correlations between the 19 items were sufficiently large for a PCA. An initial analysis was run to determine the eigenvalues for each component in the data; four PCs had eigenvalues over 1 (Kaiser's criterion); therefore, four PCs were identified. These components explained 72.3% of the variance. eTable 4 shows the factor loadings after rotation. The PCA was conducted using the package pysch in R. The 19-item beliefs/knowledge questions were transformed into four theme scores (i.e., common factors), resulting in four measurements for each participant. These theme scores are used in subsequent analyses.

1.2.5. COVID-19 vaccine hesitancy

A single-item assessed vaccine likelihood: "If the COVID-19 vaccine were easily available to you, how likely would you be to get it?". This item was measured on a six-point Likert scale (1 = 'Not at all likely' to 6 = 'Definitely likely'). Responses were reverse-scored to determine vaccine hesitancy.

1.3. Data analysis

Participants' characteristics, including demographics and decision-making assessments, were described using mean, standard deviation, frequency, and percentages, where appropriate. Univariate linear regression analyses were conducted to determine the relationship

Box 1. Individual items of COVID-19 vaccine beliefs/knowledge

1) **"The vaccine could protect me against getting COVID-19".**
2) **"If I get the vaccine, that could protect my family and friends from getting COVID-19".**
3) **"I worry that the vaccine might cause some unpleasant side effects".**
4) **"I worry that the vaccine might cause long term health effects for me".**
5) **"I worry that the vaccine might cause more harm than getting COVID-19".**
6) **"If enough other people get the vaccine, I do not need to get it".**
7) **"I am worried that the vaccine was developed too quickly".**
8) **"I am worried that I could get sick with COVID-19 by taking the vaccine".**
9) **"I would get a vaccine for COVID-19 if it was available for free to anyone who wanted it".**
10) **"I believe it is important for everyone to take the COVID-19 vaccine to help end the pandemic".**
11) **"Getting the COVID-19 vaccine is important so I can see my friends and family".**
12) **"Getting the COVID-19 vaccine is important so I can go to bars, clubs, and restaurants".**
13) **"I trust that the U.S. government approval of the vaccine means it is safe and effective".**
14) **"I am not afraid of COVID-19, so I don't think getting a vaccine is necessary".**
15) **"I am concerned I can't get the vaccine because I don't have health insurance, or my insurance won't cover the vaccine".**
16) **"I am concerned I can't get the vaccine because I don't know where or how to get the vaccine".**
17) **"Trying to get the vaccine is too complicated or is too much trouble".**
18) **"I don't plan to get the vaccine because I don't trust doctors".**
19) **"I don't need to get the vaccine because I am young and healthy".**

between the COVID-19 vaccine hesitancy (6-point Likert; dependent variable) and each of the study measures (i.e., the MCQ, the UPPS-P negative and positive urgency subscales, each of the 19 COVID-19 vaccine beliefs/knowledge statements; independent variables). An exhaustive model selection was performed to consider age, sex, in a degree program, employment status, and UPPS-P negative and positive urgency subscales, as covariates to our main effect of interest (i.e., delay discounting). The model with the lowest Bayesian Information Criterion (BIC) was considered optimal, and those covariates were used throughout subsequent analyses. Four separate multiple linear regressions were used to evaluate the association between COVID-19 vaccine hesitancy (dependent variable) and each of the four belief/knowledge themes (independent variables).

A parallel mediation analysis was performed to evaluate the mediating role of each of the four beliefs/knowledge theme scores (M1, M2, M3, M4) in the relationship between MCQ (X) on COVID-19 vaccine hesitancy (Y). The indirect effects of each of the four beliefs/knowledge themes, as well as the total indirect effect are reported. All regression analyses included the significant covariates identified from model selection. The mediation analysis was performed using the lavaan package in R (Rosseel, 2012) and reported as standardized effects and 95% confidence intervals (CI).

2. Results

2.1. Study sample and descriptive results

Participant accrual, sample size, and exclusions from the analytic sample are depicted in eFigure 1. Among 4,100 eligible 9th-grade students, 3,396 (87.7%) provided consent and enrolled in fall 2013. Data were collected for 2,801 (82.5%) participants in fall 2016 and for 2,167 (63.8%) in spring 2021. After removing missing responses and other exclusions, 1,260 (37.1%) participants comprised the analytic sample (eFigure 1). We performed a sensitivity analysis to determine potential biases resulting from lost to follow-up. Participants not included in this analysis were statistically older and had different sex and race/ethnicity compositions (*ps* < 0.001; eTable 2 in the Supplement).

Among 1,260 young adults in the analytic sample, 59.7% reported being female, 45.3% Hispanic or Latino, 20.2% Asian, and 17.2% White. They were 21.33 years old on average (±0.49) in April 2021. Participants had an average delay discounting rate ($\ln(k)$) of −4.33 (±1.29; 76-day halflife), UPPS composite score of 46.02 (±16.06) and COVID-19 vaccine hesitancy score of 2.68 (±1.82; Table 1).

2.2. Association between measures and COVID-19 vaccine hesitancy

Univariate regression was performed to identify associations of demographics, UPPS negative and positive urgency scores, and delay discounting with COVID-19 vaccine hesitancy (Table 1). Of the demographics, age ($F(1,1258) = 4.046$, $p = 0.045$), race/ethnicity ($F(7,1227) = 12.684$, $p < 0.001$), student status ($F(2,1253) = 38.231$, $p < 0.001$), and employment ($F(2,1257) = 30.262$, $p < 0.001$) were significantly associated with COVID-19 vaccine hesitancy. Delay discounting also exhibited a significant association with COVID-19 vaccine hesitancy ($F(1,1258) = 8.252$, $p = 0.004$). No significant association was found for the UPPS negative and positive urgency scores ($F(1,1258) = 1.294$, $p = 0.255$ and $F(1,1258) = 0.357$, $p = 0.550$, respectively).

To further explore the factors associated with COVID-19 vaccine hesitancy, an exhaustive model selection was performed using participant characteristics as covariates to our main effect of interest (i.e., delay discounting). The models with the lowest BIC included delay discounting and employment (delay discounting: $F(1,1256) = 5.3044$, p

Table 1
Summary of demographics, UPPS negative and positive subscales, and delay discounting, and their association with COVID-19 vaccine hesitancy. Demographics are summarized with mean (standard deviation) or frequency (percentage) where appropriate. The results of univariate regression for each variable with COVID-19 vaccine hesitancy are reported.

	Summary	Univariate analysis		
	Mean (SD)/Frequency (%)	*df*	*F*	*P*
Demographics				
Age (Mean (SD))	21.33 (0.49)	1, 1258	3.080	0.080
Gender (Frequency (%))		2, 1257	1.184	0.306
Female	752 (59.7)			
Male	460 (36.5)			
Other identity	48 (3.8)			
Race/Ethnicity (Frequency (%))		7, 1227	12.684	**<0.001**
American Indian/Alaska Native	7 (0.6)			
Asian	249 (20.2)			
Black/African American	47 (3.8)			
Hispanic or Latino	559 (45.3)			
Native Hawaiian/Pacific Islander	37 (3.0)			
White	212 (17.2)			
Other	62 (5.0)			
Multi-ethnic/multi-racial	62 (5.0)			
In a degree program (Frequency (%))		2, 1253	38.231	**<0.001**
Currently enrolled	830 (65.9)			
Not currently enrolled	392 (31.1)			
Don't know	38 (3.0)			
Employment (Frequency (%))		2, 1257	30.262	**<0.001**
Work	740 (58.7)			
Don't work	456 (36.2)			
Other	64 (5.1)			
Measures				
Delay discounting (Mean (SD))	−4.33 (1.29)	1, 1258	8.252	**0.004**
UPPS negative urgency subscale (Mean (SD))	23.77 (8.38)	1, 1258	1.294	0.255
UPPS positive urgency subscale (Mean (SD))	22.25 (9.26)	1, 1258	0.357	0.550
Variable of Interest				
COVID-19 vaccine hesitancy (Mean (SD))	2.68 (1.82)	–	–	–

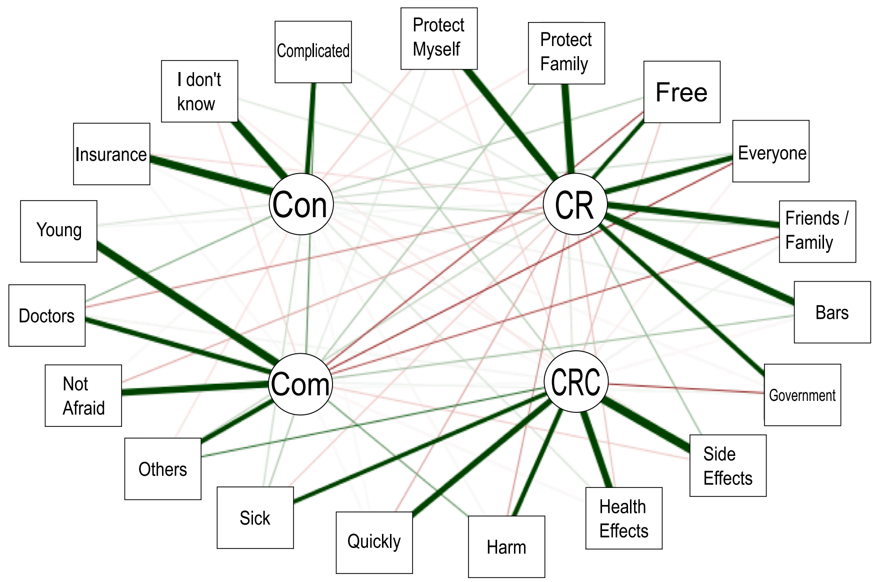

Fig. 1. Visualization of components from Principal Components Analysis. Con: *Convenience;* CR: *Collective Responsibility*; CRC: *Confidence and Risk Calculation*; Com: *Complacency*. Edge weights are proportional to factor loadings (eTable3).

= 0.02; employment: $F(2,1256) = 28.7096$, $p < 0.001$; $BIC_{optimal} = 5056.62$; $BIC_{full.model} = 5109.38$). No other covariates of interest persisted.

2.3. COVID-19 vaccine hesitancy beliefs/knowledge themes

Eighteen out of the 19 COVID-19 vaccine beliefs/knowledge measures were significantly associated with COVID-19 vaccine hesitancy (eTable 3; note only "Health Insurance" was not significantly associated). A principal components analysis (PCA) was conducted to determine common themes among these COVID-19 vaccine beliefs/ knowledge measure. In total, four themes were identified: *Collective Responsibility, Confidence and Risk Calculation, Complacency, and Convenience* (Fig. 1**;** eTable 4 for standardized factor loadings). Note that the four themes align with the 5C model. Participant-level scores for each of the four themes were significantly associated with COVID-19 vaccine hesitancy (Fig. 2, Table 2). Specifically, scores for *Collective Responsibility* (β = -1.158[-1.213,-1.102]) and *Convenience* (β = -0.132 [-0.185,-0.078]) were negatively associated with COVID-19 vaccine hesitancy. On the other hand, *Confidence and Risk Calculation* (β = 0.283 [0.230,0.337]) and *Complacency* (β = 0.412[0.358,0.466]) scores were positively associated with COVID-19 vaccine hesitancy. In addition, *Collective Responsibility* (β = -0.060[-0.101,-0.018]) was significantly negatively associated with delay discounting and *Complacency* (β = -0.063[0.021,0.105]) was significantly positively associated with delay discounting (Table 2).

3. Mediation analysis

A mediation analysis was performed to test if the vaccine beliefs/ knowledge themes (principal components) mediated the relationship between delay discounting and COVID-19 vaccine hesitancy. A mediating indirect effect of vaccine beliefs/knowledge themes was observed (Indirect effect: 0.096; [0.043, 0.149]) without a significant direct effect between delay discounting and vaccine hesitancy (Direct effect: −0.006; [-0.047, 0.035]; Fig. 3). A significant indirect effect via *Collective Responsibility* was observed (β = 0.069[0.022, 0.116]), including a negative association between delay discounting and *Collective Responsibility* (β = -0.060[-0.101, −0.019]) and a negative association between *Collective Responsibility* and COVID-19 vaccine hesitancy (β = -1.158 [-1.213, −1.103]). In addition, a significant indirect effect via *Complacency* was observed (β = 0.026[0.008, 0.044]), including a positive association between delay discounting and *Complacency* (β = 0.063[0.022, 0.104]) and a positive association between *Complacency* and COVID-19 vaccine hesitancy (β = 0.412[0.357, 0.467]). Indirect effects via *Convenience* and *Confidence and Risk Calculation* were nonsignificant (*ps* ≥ 0.119).

4. Discussion

In this study of psychological determinants of vaccine hesitancy among young adults in LA County two primary findings were observed. First, we identified four vaccine beliefs/knowledge themes: *Collective Responsibility, Confidence and Risk Calculation, Complacency,* and *Convenience*. Second, delay discounting in adolescence predicted COVID-19 vaccine hesitancy during young adulthood four years later, mediated by vaccine beliefs/knowledge themes, with a significant indirect effect via *Collective Responsibility* and *Complacency.* As previous studies have reported numerous modifiable risk factors of vaccine hesitancy (Afifi et al., 2021; Aw et al., 2021; Kreps et al., 2020; Shih et al., 2021), policymakers face a highly complex puzzle in developing effective interventions to increase vaccine uptake. Grouping multiple risk factors allows the development of integrated strategies focused on general themes that may reach more people. This study integrated multiple aspects of COVID −19 vaccine beliefs/knowledge into themes that are consistent with the 5C model of vaccine hesitancy (MacDonald and SAGE Working Group on Vaccine Hesitancy, 2015) model of vaccine hesitancy in COVID-19 related studies (Barello et al., 2021; Ingram et al., 2022; Kwok et al., 2021; Machida et al., 2021) and vaccine hesitancy generally (Betsch et al., 2018, 2015; Larson et al., 2014; WHO, 2016; Wiysonge et al., 2022).

Our findings show an effect of CNDS regulation (as measured by delay discounting) in adolescence predicts vaccine hesitancy 4-years later in young adulthood (Fig. 3), mediated by *Collective Responsibility* *(*Fig. 3*; 1st path 1st portion)* and *Complacency (*Fig. 3*; 3rd path 1st portion)*. According to the CNDS theory, an immediacy bias (i.e., higher delay

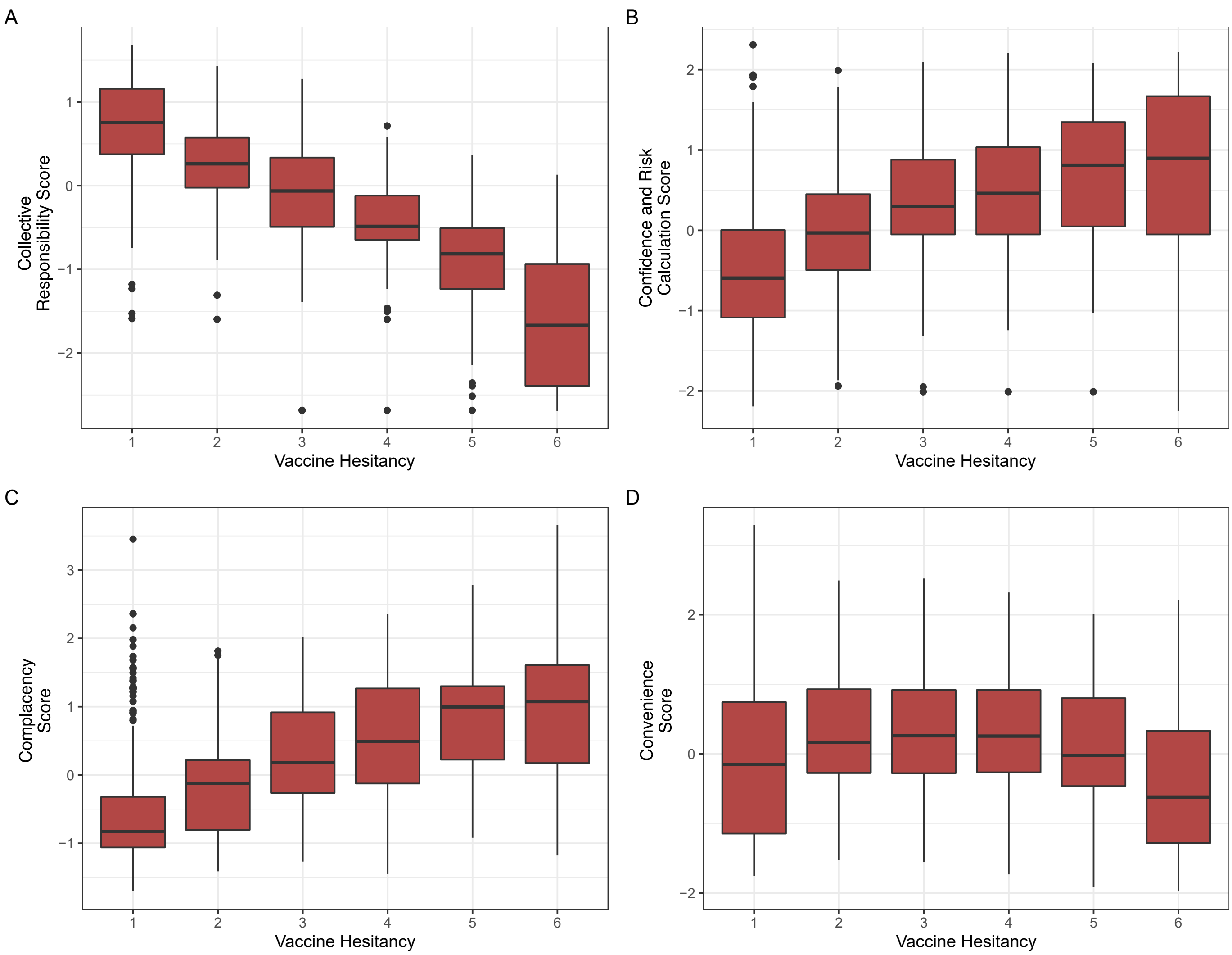

Fig. 2. Boxplots of vaccine beliefs/knowledge themes by vaccine hesitancy.

Table 2
Regression results for the association between theme scores and COVID-19 vaccine hesitancy and MCQ. All analyses included the employment group as a covariate.

	COVID-19 vaccine hesitancy		MCQ	
Themes	Coefficient	95% CI	Coefficient	95% CI
Collective Responsibility	**−1.158**	**−1.213, −1.102**	**−0.060**	**−0.101, −0.018**
Confidence and Risk Calculation	**0.283**	**0.230, 0.337**	0.019	−0.024, 0.062
Complacency	**0.412**	**0.358, 0.466**	**0.063**	**0.021, 0.105**
Convenience	**−0.132**	**−0.185, −0.078**	0.036	−0.007, 0.079

discounting) results when greater relative activity is seen by the hyperactive-impulsive neural system relative to the hypoactive-executive neural system (McClure et al., 2004). Specifically, an immediacy bias was associated with lower *Collective Responsibility* scores and higher *Complacency* scores. Lower C*ollective Responsibility* being associated with higher discounting rates is consistent with extant literature demonstrating that individuals who prefer to solely receive a reward compared to sharing a larger reward with a group have higher discounting rates (Bickel et al., 2014a). Higher complacency scores being associated with higher discounting rates is aligned with health-related literature demonstrating that individuals with an immediacy bias tend not to integrate temporally extended prosocial reinforcers into decision-making (Bickel et al., 2014b). For example, complacent individuals who think they do not need a vaccine because they are young and healthy neglect to consider the delayed benefits of getting the vaccine. This result is also consistent with Wismans et al. (2021), who showed *Complacency* was the only 5C theme that mediated the relationship between delay discounting and vaccine intention in an European sample over a 6-month period when COVID vaccines were not yet authorized. Together, these two themes potentially reflect an individual's perceived value of the personal and collective long-term benefits of getting the vaccine and suggest that interventions to promote CNDS regulation may decrease vaccine hesitancy.

CNDS regulation (i.e., as measured by delay discounting) tend to be stable (Felton et al., 2020; Martínez-Loredo et al., 2017) or modestly decrease throughout adolescence (Anokhin et al., 2015). Experimental interventions have effectively modulated CNDS regulation. For example, contingency management (Bickel et al., 2010; Fletcher et al., 2014) has been shown to decrease control of the impulsive system, while working memory training (Bickel et al., 2011b; McClure et al., 2004; Olesen

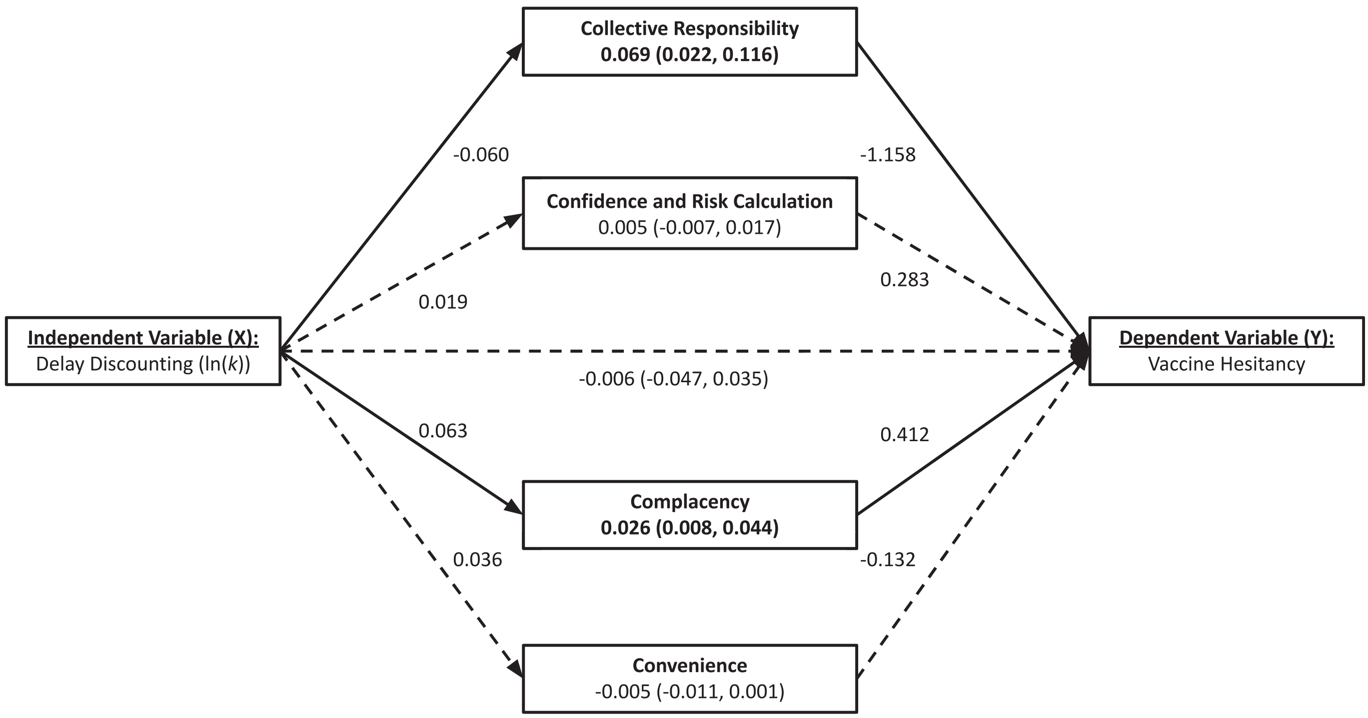

Fig. 3. Diagram for the mediation of vaccine beliefs/knowledge themes on the relationship between delay discounting rate (X) and vaccine hesitancy (Y). Estimates and 95% CI of the indirect and direct effects when considering vaccine beliefs/knowledge themes and standardized regression coefficients of each path component are included. Significant indirect effects are represented with solid path arrows, and non-significant indirect effects are represented with dashed path arrows. Employment status was included as a covariate.

et al., 2004), and episodic future thinking (EFT; Daniel et al. 2013; EFT; Athamneh et al. 2020; Snider et al. 2016; Stein et al. 2016) have effectively increased control of the executive system. Many interventions that target underlying decision-making processes are amenable to remote delivery (e.g., EFT) and can be implemented nationwide alone or as an adjuvant strategy to significantly impact public health. This work suggests that interventions to promote CNDS regulation may be a valuable public health strategy to decrease vaccine hesitancy.

In addition to the above, we found that misinformation related to *Collective Responsibility (*Fig. 3*; 1st path 2nd portion)* and *Complacency (*Fig. 3*; 3rd path 2nd portion)* drove higher vaccine hesitancy scores. Consistently, other studies (Tavolacci et al., 2021; Wismans et al., 2021) found that collective responsibility was associated with higher vaccine hesitancy among young adults. Only Wismans et al reported a relationship between complacency and vaccine hesitancy. Importantly, these other studies found confidence was an important factor related to vaccine intention while ours did not. Together, our findings suggest that public health messaging should prioritize actions to address misinformation to increase *Collective Responsibility* and decrease *Complacency* among those with risk-enhancing CNDS traits. For example, by correcting messages about vaccine effectiveness (Barua et al., 2020; CDC, 2021b; Murthy, 2021; Office of the U.S. Surgeon General, 2021), highlighting the importance of immunity to protect oneself and to altruistically protect others including those most susceptible, family and friends and to achieve herd immunity (Pfattheicher et al., 2021), and clarifying susceptibility to COVID-19 among young adults (Kuehn, 2021; Rumain et al., 2021). Further, public health campaigns might benefit from specifically targeting platforms and places young adults frequent, such as through social media campaigns (Hussong et al., 2021; Puri et al., 2020) - where misinformation is high (Basch et al., 2021; Burki, 2020; Frenkel et al., 2020) - and colleges (Finney Rutten et al., 2021). As future scenarios estimate, mitigating vaccine hesitancy and misinformation is crucial to containment and prevention because COVID-19 may never be fully eradicated (Skegg et al., 2021).

Although not our main finding, we report that the COVID-19 belief/knowledge health insurance statement was the only statement not associated with vaccine hesitancy. One potential explanation is that at the time of the 2nd data collection, COVID-19 vaccines were already available for free in the US regardless of insurance status (State of California, 2023). In addition to delay discounting, we found that employment predicted vaccine hesitancy. Previous literature have demonstrated delay discounting is robustly related to economics - both individual circumstances (Agrawal et al. 2023) and the wider environment (Ruggeri et al. 2022). For example, under current or anticipated financial hardship, individuals are more likely to engage in delay discounting (Hilbert et al. 2022). Understanding the interplay between these factors is important for public health efforts aimed at promoting vaccine uptake, particularly in populations that may be more vulnerable to financial stress or other social determinants of health. Moreover, despite delay discounting and UPPS-P being frequently used as indices of impulsive decision-making patterns, our finding suggests that behavioral (implicit-like) decision measures might provide unique information that holds enduring predictions across time and developmental stages non-redundant with personality-type measures of decision making like UPPS-P.

5. Limitations

This study has several limitations. First, the study targeted young adults, used a convenience sample from Los Angeles, CA, and excluded participants who did not have complete data resulting in demographic differences between the analytic and excluded samples. Whether findings generalize to other locations or age ranges is unknown. Second, although broad, the list of statements to assess vaccine beliefs/knowledge was not exhaustive. Third, data from this study were collected before the majority of the US population was vaccinated. Demonstrations of effectiveness were apparent for both safety and benefit of preventing serious harm (other than efficacy in the Phase III clinical trials).

The extent the associations observed were attenuated or exacerbated for this reason is unknown. Fourth, while the mediation analysis includes longitudinal data, we did not account for temporal changes in the mediational process. Thus, interpretation of the causal pathway of these mediation results is limited. Lastly, as vaccination hesitancy is context-, time-, place-, and vaccine-related (Dubé et al., 2014), this snapshot of vaccine hesitancy may have changed since April 2021. Additional research on intentions to vaccinate and its determinants is needed for COVID-19 and other disease-related vaccines.

6. Conclusions

This study shows evidence that a fairly stable, neurobehaviorally underpinned decision-making tendency originating in adolescence might confer risk for vaccine hesitancy via broader social-contextual themes of *Collective Responsibility* and *Complacency*. Our study further explains the relationship between *meso*-level influences and micro-level determinants of individual vaccine-related decision-making among young adults. These findings pave the way for developing effective public health and psychological interventions that may target these highly modifiable constructs to increase vaccine intention.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Although the following activities/relationships do not create a conflict of interest pertaining to this manuscript, in the interest of full disclosure, Dr. Bickel would like to report the following: W. K. Bickel is a principal of HealthSim, LLC; BEAM Diagnostics, Inc.; and Red 5 Group, LLC. In addition, he serves on the scientific advisory board for Sober Grid, Inc.; and Ria Health; serves as a consultant for Boehringer Ingelheim International and Lumanity; and works on a project supported by Indivior, Inc. Dr Tegge would like to report work on a project supported by Indivior, Inc. The other authors report no conflict of interest.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pmedr.2023.102280.

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