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Cognitive underpinnings of COVID-19 vaccine hesitancy

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ABSTRACT

Rationale: Vaccines save lives. Despite the undisputed value of vaccination, vaccine hesitancy continues to be a major global challenge, particularly throughout the COVID-19 global pandemic. Since vaccination decisions are counter-intuitive and cognitively demanding, we propose that vaccine hesitancy is associated with executive function—a group of high-level cognitive skills including attentional control, working memory, inhibition, self-regulation, cognitive flexibility, and strategic planning.
Objective: We set out to test (i) whether vaccine hesitancy is driven by individual differences in executive function beyond established socio-demographic factors (e.g., education, political orientation, gender, ethnicity, age, religiosity) and depressed mood, and (ii) whether this relationship is exacerbated by situational stress.
Methods: Two studies were conducted with U.S. residents. Using a cross-sectional design, Study 1 examined the associations between executive function, socio-demographic factors, COVID-19 conspiracy beliefs, trust in health authorities, and COVID-19 vaccine hesitancy. Using an experimental design, Study 2 focused solely on unvaccinated individuals and tested the interactive effect of executive function and stress on willingness to receive a COVID-19 vaccine. We used ordinal logistic regressions to analyze the data.
Results: Individual differences in executive function predicted participants' COVID-19 conspiracy beliefs, trust in health authorities, and their willingness to vaccinate against COVID-19. Importantly, the unique contribution of executive function to vaccine hesitancy could not be explained by socio-demographic factors or depressed mood. Furthermore, Study 2 revealed that weaker executive function had detrimental effects on COVID-19 vaccine acceptance and trust in health authorities mainly under heightened stress.
Conclusions: Individual differences in executive function and situational stress jointly impact COVID-19 vaccination decisions and need to be considered together when designing health communications aimed at reducing COVID-19 vaccine hesitancy. Interventions that lower stress and promote trust have the potential to increase vaccine acceptance, especially for individuals with weaker executive function.

1. Introduction

COVID-19 vaccination efforts continue worldwide. Although multiple effective vaccines were rapidly developed in the aftermath of the COVID-19 outbreak, their success is predicated on vaccine acceptance. Recent reports show that a notable proportion of the global population is still hesitant to accept COVID-19 vaccines (Hyland et al., 2021; Lazarus et al., 2021; Murphy et al., 2020; Schwarzinger et al., 2021). Such *vaccine hesitancy*, defined as "the refusal or delay in being vaccinated despite safety assurance and availability of vaccination services" (MacDonald, 2015), continues to be a major threat to public health (Burger et al., 2021). Current estimates indicate that COVID-19 vaccine hesitancy can lead to substantial societal health and economic costs, including unnecessary deaths and prolonged lockdowns (Mesa et al., 2021). Moving forward, to achieve herd immunity and ultimately overcome COVID-19, a substantial proportion of the population needs to be vaccinated (WHO, 2020). Thus, it is imperative to understand the factors underlying vaccine hesitancy.

Recently, extensive research has documented socio-demographic underpinnings of COVID-19 vaccine hesitancy, including gender, ethnicity, education, political orientation, and spatial or income disparities (e.g., Callaghan et al., 2021; da Fonseca et al., 2021; Liu and Li, 2021; Savoia et al., 2021). Despite these efforts to uncover the drivers of COVID-19 vaccine hesitancy, only scant research examined its cognitive underpinnings. For instance, recent work shows that cognitive function and style impact vaccination decisions (Batty et al., 2021; Martinelli and

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Veltri, 2021) and that working memory shapes compliance with social distancing (Xie et al., 2021). Relatedly, an emergent research stream examined how susceptibility to misinformation and conspiracy beliefs influences vaccine hesitancy (Đorđević et al., 2021; Romer and Jamieson, 2020). Drawing on this work, we sought to better understand the interplay between cognition and COVID-19 vaccine acceptance by examining the role of executive function.

1.1. Cognition and vaccine hesitancy

In 2019, the World Health Organization (WHO) classified vaccine hesitancy as one of the top ten threats to global public health (WHO, 2019). This threat is due in part to the fact that the value of vaccination is highly counterintuitive and cognitively demanding to accept (Damnjanović et al., 2018; Milton et al., 2015).

Moreover, vaccine hesitancy has been exacerbated during the current pandemic by an accompanying "infodemic", an overabundance of information as well as misinformation (Frenkel et al., 2020; Galloti et al., 2020), which is likely to make vaccination decisions even more challenging at a cognitive level. In this context, since vaccination-related decisions entail complex and demanding mental processes that may hinge on one's cognitive ability to compare and integrate multiple pieces of potentially overwhelming information, weaker cognitive skills may undermine vaccine acceptance.

Relatedly, prior research has suggested that correlates of cognition, such as education or health literacy, also impact risk perception and preventive behaviors (Hicks, 2022; Lipkus et al., 2001; Mouter et al., 2022; Rothman et al., 2008). Extending this research stream, we examined how executive function shapes COVID-19 vaccine acceptance.

1.2. Executive function

A key facet of cognition is *executive function* (EF), which refers to a host of interrelated higher-order cognitive processes that entail effortful, top-down control of action, attention, and self-regulation, including core functions like working memory, inhibition, and cognitive flexibility (Diamond, 2013). These functions are integral to better decision-making, as EF plays a critical role in enabling forethought, planning, and goal achievement (Miyake and Friedman, 2012). Hence, previous research shows that stronger EF is robustly associated with desirable health, achievement, wealth, and quality of life outcomes (Diamond, 2013).

EF has also been shown to correlate with highly critical health outcomes, such as better chronic disease prevention, superior treatment adherence, and higher psychological well-being (Luerssen and Ayduk, 2017; Ramírez-Luzuriaga et al., 2021). In the domain of health behaviors that require impulse control, such as eating, weaker EF has been associated with more impulsive behaviors and obesity (Capelli et al., 2019; Diamond, 2013; Hoffman et al., 2012). Following this reasoning, we posit that beyond positively contributing to health decision-making, stronger EF will enable individuals to engage in flexible thinking and overcome the reduced level of public trust inherent in the current COVID-19 infodemic. Conversely, we contend that weaker EF will lead to higher vaccine hesitancy.

1.3. Executive function, stress, and vaccine hesitancy

Extant research suggests that due to its finite capacity, EF can be impaired by the detrimental effects of situational stress (Girotti et al., 2018; Shields et al., 2016). Specifically, high stress reduces working memory-related activity and weakens the mental capacity and cognitive flexibility needed for adapting behavior to changing circumstances (Starcke et al., 2016). Conversely, stronger EF renders individuals more resilient to such stress-induced adverse effects (Girotti et al., 2018).

On these premises, we broadly posited that weaker EF will be associated with higher vaccine hesitancy. We further hypothesized that EF and stress will have an interactive effect such that EF will play an increasingly critical role in vaccination decisions under stress.

Our hypotheses resonate with prior empirical findings that demonstrate that performance on various executive function tasks predicts cognitively demanding health behaviors such as chronic disease prevention (Hall and Marteau, 2014), smoking cessation, alcohol consumption, and sleeping, superior treatment adherence, particularly for complex regimens (Hinkin et al., 2002; Stilley et al., 2010), physical activity (Daly et al., 2015), and even compliance with social distancing during the COVID-19 outbreak (Xie et al., 2020). To test whether the proposed effects are explained solely by socio-demographic factors or depressed mood, we measured and statistically controlled for a host of such factors across both studies.

2. Methods and results

We conducted two studies with U.S. residents in April–May 2021 using Amazon's Mechanical Turk (MTurk), an online participant pool commonly employed for data collection in social science research (Paolacci et al., 2010) including vaccination research (Carpiano and Fitz, 2017; Ling et al., 2019; Sarathchandra et al., 2018) and specifically COVID-19 research (Latkin et al., 2021). We relied on this participant pool as MTurk samples entail higher demographic diversity and stable demographic characteristics relative to other online-based convenience samples (Buhrmester et al., 2011; Moss et al., 2020). Moreover, to recruit our participants on MTurk (Young and Young, 2019), we used CloudResearch (formerly TurkPrime), which enables researchers to collect data from real participants by verifying their authenticity (Hauser et al., 2021). While CloudResearch also allows for targeting specific demographic and psychographic groups, we did not use these features for our study targeting the general U.S. population. All respondents were rewarded with $1 for their participation.

2.1. Variables included in both studies

The following variables were common across both studies: (i) the independent variable; (ii) the dependent variable; and (iii) socio-demographic variables, depressed mood, and attitudinal variables. Below we provide a detailed description of these variables.

2.1.1. Key independent variable

Our main predictor is executive function (EF). To capture this variable, across both studies we employed the Stroop Color Task (Stroop, 1935). Developed almost a century ago, this task has been the mainstay measure of individual differences in EF, including cognitive flexibility, selective attention, processing speed, and working memory (for a review see MacLeod, 1991).

In this task, the participants were instructed to name the color of words displayed on their screen by pressing a corresponding key on their keyboards ("R" for red and "B" for blue). Before completing the actual task, participants went through 10 practice trials with correct vs. incorrect feedback following each trial response. The actual Stroop Task consisted of 60 trials without feedback, namely 20 congruent trials (word "BLUE" written in blue color and word "RED" written in red color), 20 neutral trials (XXX written in either blue or red color), and 20 incongruent trials ("BLUE" written in red color and "RED" written in blue color) all randomized. The response time was self-paced, and each stimulus remained on the screen until participants responded. However, before commencing, participants were instructed to respond as quickly and accurately as possible, without interruptions, in one sitting (Fig. 1a–c).

Stroop performance was measured through reaction times (RT) per trial, recorded sensitively using a Javascript code. Average Stroop RT was computed for all trials, incongruent, congruent, and neutral trials separately. The difference in RT between neutral and congruent trials versus incongruent trials was calculated as a measure of inhibitory

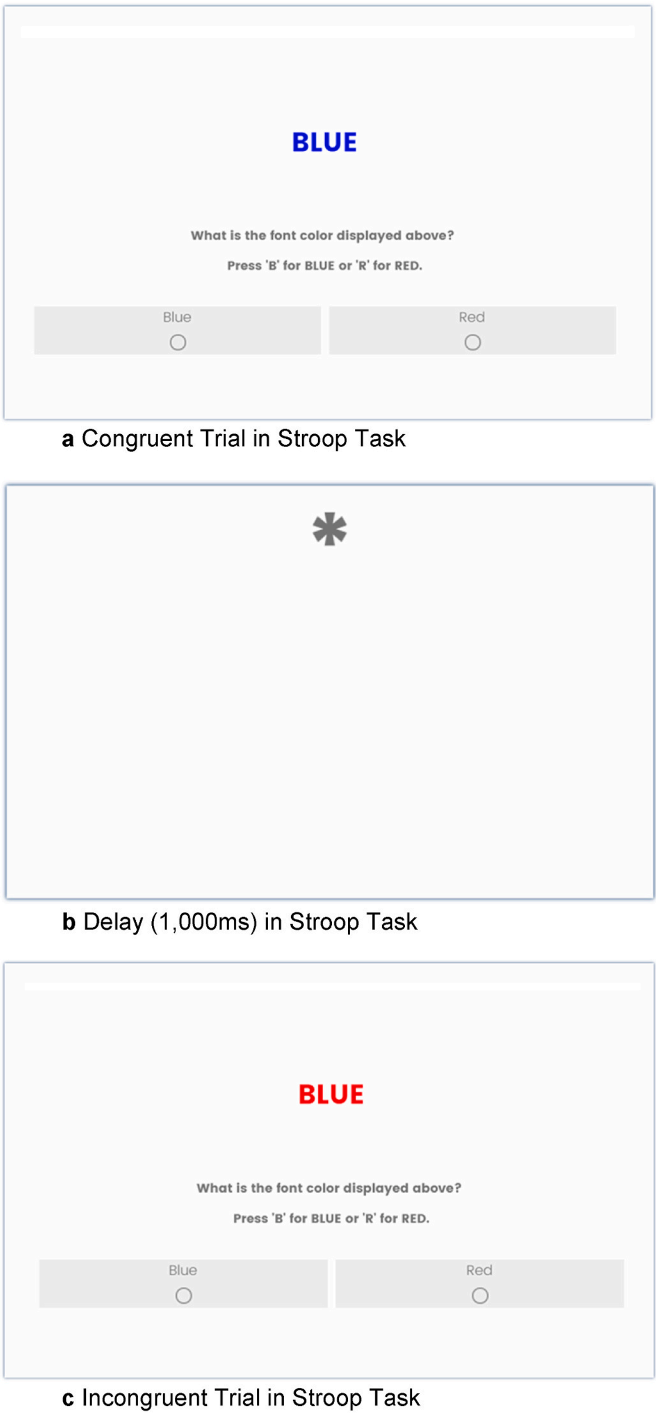


Fig. 1. **a)** Congruent Trial in Stroop Task. **b)** Delay (1,000 ms) in Stroop Task. **c)** Incongruent Trial in Stroop Task.

ability, known as the *Stroop Interference* (MacLeod, 1991).

At the end of the Stroop Task, we used two screening questions to identify participants who were interrupted during the task due to technical or other reasons. This was important to include as we did not have complete control over participants' equipment, surroundings, or internet connection, which could also influence their response times. Participants who self-reported having had interruptions during the Stroop Task (Study 1 = 48, Study 2 = 35) were removed from the final sample before any analyses were conducted.

Additionally, 16 participants in Study 1 (3.5%) and 12 participants in Study 2 (2.5%) were excluded for spending excessive time on the Stroop Task as in similar studies (e.g., Xie et al., 2020), which relied on response times from online participant pools (defined as above 5 std per trial or above 2 std on all trials). Despite the key role of Stroop Response Times accuracy in our theorizing, we chose not to impute missing values, and hence, we excluded them from the analyses. There were no other missing data values in any of the two samples. Therefore, the final samples consisted of 435 participants in Study 1 (254 females, age: M = 44.16, SD = 13.78) and 453 participants in Study 2 (304 females, age: M = 38.65, SD = 12.45). Note that the exclusion percentage is rather conservative and lower than other cognitive studies using online samples (e.g., Xie et al., 2020). Before conducting any analyses, however, the missing data were examined. As previous research on missing values shows, missing values due to technical problems imply that missing completely at random (MCAR) could be considered as the missing data mechanism (Sidi and Harel, 2018). Little's MCAR test indeed indicated that values were missing completely at random with respect to all other variables included in the analyses in both Study 1 and Study 2 (both $ps > 0.10$), giving us additional assurance that our data were not systematically biased by missing data.

2.1.2. *Key dependent variable*

In both studies, the key dependent variable of vaccine hesitancy was measured using a Likert-type item. Specifically, the unvaccinated participants were asked whether they were considering getting vaccinated against COVID-19 on a 5-point scale. Response options were ordered as follows: 1 = Definitely Not, 2 = Probably Not, 3 = Undecided, 4 = Probably Yes, 5 = Definitely Yes. At the end of the studies, all participants were debriefed and those participants who did not answer either "Definitely Yes" or "Probably Yes" were provided with resources from the Centers for Disease Control and Prevention (CDC, 2020) on COVID-19 vaccination (https://www.cdc.gov/vaccines/covid-19/index.html).

2.1.3. *Covariates and control variables*

We measured a host of socio-demographic variables known to impact COVID-19 behaviors and included them in the analyses as covariates and control variables. Specifically, these variables were the following: age, gender, ethnicity, education, income, political orientation. Additionally, we measured depressed mood (PHQ; Spitzer et al., 1999; 9 items on a 5-point scale, $\alpha = 0.93$ in Study 1, $\alpha = 0.92$ in Study 2). Further details about the socio-demographic information of the participants can be found in Supplementary Table S1.

2.1.4. *Attitudinal variables*

We also measured participants' general attitudes towards vaccination via the *Vaccination Attitudes Scale* (VAX; Martin and Petrie, 2017), which included 12 items such as "Although most vaccines appear to be safe, there may be problems that we have not yet discovered" (reverse-coded; 1 = Strongly Disagree; 5 = Strongly Agree, $\alpha = 0.94$ in Study 1, $\alpha = 0.91$ in Study 2).

Trust in authorities. Participants reported the extent to which they trust the government, doctors, scientists, and the WHO on a 5-point scale (1 = Never Trust; 5 = Always Trust; $\alpha = 0.82$ in Study 1, $\alpha = 0.77$ in Study 2).

To measure *COVID-19 conspiracy beliefs*, we gathered 12 popular conspiracy beliefs surrounding the COVID-19 pandemic, all of which broadly contained an underlying belief that the pandemic cannot have happened by itself and that it was somehow controlled and concealed by unjust or unaccountable powers (1 = Definitely False; 5 = Definitely True, $\alpha = 0.90$ in Study 1, $\alpha = 0.88$ in Study 2).

Additional measures comprised exploratory variables related to the COVID-19 pandemic, not included in the current research. These were general conspiracy beliefs, COVID-19 fear, planned consumption behavior, and compliance with COVID-19 mitigation measures. Further details and all the scale items can be found in Supplementary Table S2.

2.1.5. Statistical analyses

We conducted ordinal regression analyses to study the association between the independent variables and willingness to receive a COVID-19 vaccine (dependent variable). Following recent research employing similar measurements of vaccine hesitancy as their dependent variable (e.g., Savoia et al., 2021; Murphy et al., 2021), results were interpreted with a range of values from 1 (high hesitancy) to 5 (low hesitancy) maintaining the original, ordinal order of the answer options without grouping the answers into categories. The parallel regression assumption for the ordinal logistic model (all $ps > 0.05$) and the goodness-of-fit of the models (all $ps < 0.05$) showed that the models were appropriate.

2.2. Study 1

2.2.1. Method

Study 1 employed a cross-sectional study design to gather data from both vaccinated and unvaccinated individuals. Its objective was to investigate (i) the differences between vaccinated and unvaccinated participants, and (ii) the associations between the participants' executive function and their vaccination-related attitudes, including general vaccination attitudes (VAX), beliefs in COVID-19 conspiracy theories, trust in health authorities, and their willingness to get vaccinated against COVID-19, after controlling for socio-demographic variables. Data collection took place on April 9–10, 2021 when vaccination was not yet available for all Americans.

2.2.2. Procedure

First, participants completed the Stroop Task, which captured individual differences in executive function. Second, they answered a questionnaire that included socio-demographic variables and assessed their depressed mood, general vaccination attitudes, COVID-19 conspiracy beliefs, trust in health authorities, whether they already received a COVID-19 vaccine, and for those who had not been vaccinated, their willingness to receive a vaccine against COVID-19. Questions and response choices were kept short using Likert-type rating scales to facilitate completion. All questions except for the ones measuring response times had a forced response requirement to avoid missing responses.

2.2.3. Results of Study 1

Willingness to get vaccinated (Fig. 2). The unvaccinated participants (n = 233) considered getting vaccinated against COVID-19 as follows: 54 (23.2%) answered "Definitely Not", 35 (15%) answered "Probably Not", 40 (17.2%) answered "Undecided", 36 (15.5%) answered "Probably Yes", and 68 (29.2%) answered "Definitely Yes". These vaccine acceptance levels were comparable to vaccine hesitancy reports from other studies conducted during similar time periods (e.g., Murphy et al., 2021).

Stroop performance. Average Stroop RT were computed for all trials ($M = 0.81$s, $SD = 0.33$s), incongruent ($M = 0.87$s, $SD = 0.38$s), congruent ($M = 0.81$s, $SD = 0.34$s), and neutral trials ($M = 0.76$s, $SD = 0.33$s) separately. The difference in RT between neutral and congruent trials versus incongruent trials ($M = 0.09$s, $SD = 0.16$s) was calculated as a measure of inhibitory ability, known as the Stroop Interference. Fig. 3 plots all Stroop performance measures across various levels of willingness to vaccinate.

Comparison of vaccinated vs. unvaccinated participants. The vaccinated ($n = 202$) and unvaccinated ($n = 233$) participants were compared to examine whether they significantly differed in any other aspects besides vaccination. T-test and chi-square results revealed that unvaccinated (vs. vaccinated) participants had significantly higher levels of general and COVID-19 conspiracy beliefs, Republican orientation, younger age, lower levels of education, income, less positive vaccination attitudes (VAX), and lower trust in authorities (all $ps < .05$). There were also marginally significant differences in terms of religiosity, depressed mood, Black ethnicity (all $ps < .10$). Nevertheless, there were no significant differences between the two groups in Stroop performance measures or gender (all $ps > .50$) at the time of data collection (early April 2021) when vaccination was not yet available for all Americans. Overall, these differences indicate that vaccination is critical not only for immunization purposes, but also for other individual and public health reasons (e.g., general vaccination attitudes) that differed significantly between vaccinated and unvaccinated individuals.

Unvaccinated participants. Next, we focused on the unvaccinated participants. First, we ran bivariate correlations to examine the relationships between Stroop RT, the above-mentioned attitudinal measurements, and willingness to get vaccinated against COVID-19. Willingness to get vaccinated correlated significantly with Stroop RT, general vaccination attitudes (VAX), trust in authorities, and both general and COVID-19 conspiracy beliefs (Supplementary Table S5). Once again, the bivariate correlations indicated that willingness to get vaccinated against COVID-19 is not an independent decision but rather a decision that is associated with several other phenomena important for both individual and public health.

To test whether Stroop RT predicted willingness to get vaccinated against COVID-19 beyond demographic variables, we employed Ordinal Logistic Regressions. First, we ran Simple Ordinal Logistic Regressions to examine to what extent each predictor influenced the dependent variable of willingness to receive a COVID-19 vaccine. For an easier interpretation of the results, we used standardized values for all the continuous variables.

Next, we ran Multiple Ordinal Regressions using a $p < 0.05$ as the criterion for inclusion of the variables in the multiple ordinal regression model. These analyses revealed that the behavioral intention of unvaccinated participants to get vaccinated against COVID-19 was best predicted by male (vs. female) gender, education, income, Democratic (vs. Republican) political orientation, religiosity, ethnicity (Black vs. All others), and their Stroop RT. Specifically, a single unit (s) increase in

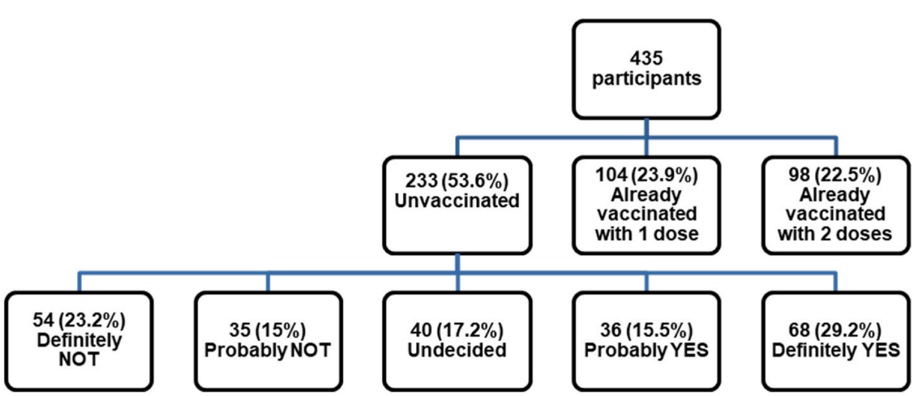
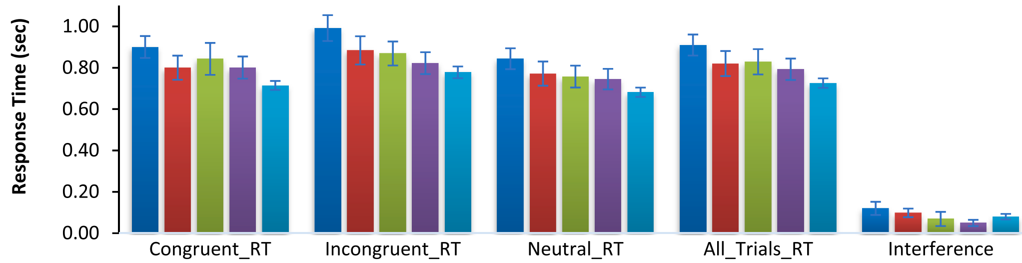


Fig. 2. Response Frequencies for willingness to get vaccinated (Study 1).



	Congruent_RT	Incongruent_RT	Neutral_RT	All_Trials_RT	Interference
Definitely Not (n = 54)	0.90	0.99	0.84	0.91	0.12
Probably Not (n = 35)	0.80	0.88	0.77	0.82	0.10
Undecided (n = 40)	0.84	0.87	0.76	0.83	0.07
Probably Yes (n = 36)	0.80	0.82	0.75	0.79	0.05
Definitely Yes (n = 68)	0.71	0.78	0.68	0.73	0.08

Fig. 3. Mean Stroop Task Reaction Times for different levels of willingness to receive a vaccine against COVID-19 among unvaccinated participants in Study 1 (1 = Definitely Not; 5 = Definitely Yes). Bars represent standard errors.

Stroop RT was associated with a 1.03 increase in log odds of willingness to get vaccinated outcome having a lower value (B = −1.03, *SE* = 0.39, OR = 0.36, 95% CI from 0.17 to 0.79, *p* = 0.01), translating into 64% decreased odds of reporting a higher level of willingness to receive a vaccine against COVID-19. Therefore, as hypothesized, weaker executive function, captured by longer Stroop RT, had a unique contribution to predicting a lower willingness to get vaccinated against COVID-19 (Table 1).

Finally, we conducted additional analyses. In these analyses, we also included the vaccinated participants in the sample and ran hierarchical linear regressions predicting the whole samples' attitudinal measurements, namely general vaccination attitudes (VAX), COVID-19 conspiracy beliefs, and trust in health authorities. The results of these analyses further provided support for the predictive power of Stroop RT. We report the results of this alternative analysis in the supplementary material, as a robustness check.

Table 1
Predicting willingness to get vaccinated among the unvaccinated participants against COVID-19 in Study 1 (N = 233).

	Simple OLR Models				Multiple OLR Model			
Independent Variable	B	SE	OR	95% C.I.	B	SE	OR	95% C.I.
Age								
Age (in years)	−0.01	0.01	–	–	–	–	–	–
Gender								
Male (0) vs. Female (1)	−1.12 **	0.25	0.33	0.20 to 0.53	−0.88 **	0.27	0.42	0.25 to 0.71
Sexual Orientation								
Heterosexual (1) vs. all other (0)	−0.55	0.44	–	–	–	–	–	–
Education								
Less than High school	−0.63	0.83	–	–	−1.25	0.96		
High school	−1.3 **	0.49	0.27	0.10 to 0.70	−1.28 *	0.54	0.28	0.10 to 0.80
Some college	−0.69	0.39	–	–	−0.74	0.44		
College	−0.23	0.38	–	–	−0.43	0.43		
Some graduate	−1.02	0.80	–	–	−1.28	0.80		
Graduate degree	–	–	–	–	–	–	–	–
Ethnicity								
White vs. all other	0.44	0.29	–	–	–	–	–	–
Black vs. all other	−1.13	0.41	0.32	0.14 to 0.72	−1.20 **	0.46	0.30	0.12 to 0.74
Asian vs. all other	0.09	0.39	–	–	–	–	–	–
Hispanic vs. all other	−0.23	0.50	–	–	–	–	–	–
Income								
Below 20 K	−1.07 *	0.49	0.34	0.13 to 0.90	−1.13 *	0.55	0.32	0.11 to 0.95
20 K–39 K	−0.55	0.50		–	−0.49	0.55		
40 K–59 K	−0.69	0.49		–	−0.88	0.54		
60 K–79 K	−0.57	0.53		–	−0.83	0.59		
80 K–99 K	−0.31	0.59		–	−0.40	0.64		
≥100 K	-	-			-	-	-	-
Political orientation								
Democrat (0) vs. Republican (1)	−1.30 **	0.25	0.27	0.17 to 0.44	−1.38 **	0.28	0.25	0.15 to 0.43
Religiosity								
Religiosity (slider 0–10)	−0.16 **	0.03	0.85	0.80 to 0.90	−0.06	0.04	–	–
Depressed Mood								
PHQ	0.03	0.16	–	–	–	–	–	–
Stroop Performance Measures								
Congruent Trials Response Time	−0.88 **	0.34	0.42	0.21 to 0.81	–	–	–	–
Incongruent Trials Response Time	−1.05 **	0.32	0.35	0.19 to 0.66	–	–	–	–
Neutral Trials Response Time	−1.04 **	0.37	0.35	0.17 to 0.74	–	–	–	–
All Trials Response Time	−1.05 **	0.36	0.35	0.17 to 0.70	−1.03 **	0.39	0.36	0.17 to 0.77
Stroop Interference	−1.07	0.70	–	–	–	–	–	–
					$\chi2$ (15) = 88.57, *p* < 0.001			

Simple and multiple variable models using Ordinal Logistic Regressions (OLS), * *p* < 0.05. ** *p* < 0.01.

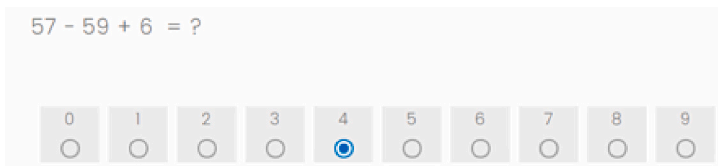
2.3. *Study 2*

In our theorizing, drawing on previous research on the detrimental effects of stress mainly for individuals with weaker EF (Girotti et al., 2018), we argued that EF and stress would have an interactive effect on vaccine hesitancy. To test this hypothesis, Study 2 extended the findings of Study 1 by (i) using an experimental approach, and (ii) focusing solely on unvaccinated individuals. Specifically, we examined the interactive effect of EF (as measured by Stroop RT) and situational stress on willingness to receive a COVID-19 vaccine.

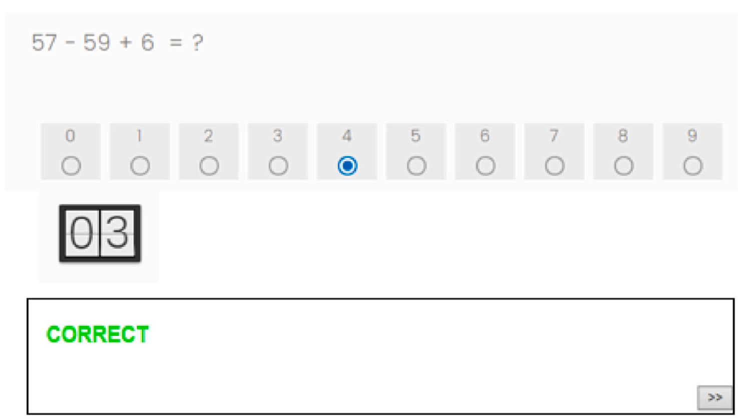
2.3.1. *Procedure*

All participants started with demographic questions, whereby they also reported whether they had received a vaccine dose against COVID-19. Participants who answered, “No” proceeded to Study 2, whereas those who answered either “Yes – 1 dose” or “Yes – 2 doses” proceeded to another study with similar length and payment.

Besides the measurements in Study 1, Study 2 examined two additional variables. First, we included an additional cognitive variable, namely Cognitive Reflection, which reflects one’s willingness to think analytically vs. intuitively (CRT; 3 items, Frederick, 2005). As recent research demonstrated that a higher CRT score was associated with higher COVID-19 vaccine intentions (Murphy et al., 2020; Martinelli and Veltri, 2021) we tested whether Stroop performance had predictive power beyond CRT. Second,and more importantly, we experimentally manipulated situational stress to test our hypothesis.



a Sample Question from the “Mental Game” (Low-Stress Condition: no time pressure, no feedback)



b Sample Question from the “Mental Game” (High-Stress Condition: time pressure and feedback for correct response)

c Sample Question from the “Mental Game” (High-Stress Condition: time pressure and feedback for incorrect response)

Fig. 4. a) Sample Question from the “Mental Game” (Low-Stress Condition: no time pressure, no feedback). **b)** Sample Question from the “Mental Game” (High-Stress Condition: time pressure and feedback for correct response). **c)** Sample Question from the “Mental Game” (High-Stress Condition.

2.3.2. Stress manipulation

We used a procedure called the "Mental Game" to experimentally manipulate stress. This was an arithmetic test based on The Montreal Imaging Stress Task (Dedovic et al., 2005)—an established protocol for inducing moderate psychological stress. The game consisted of 20 computerized mental arithmetic questions preceded by 3 practice items. Participants were randomly assigned to either the high stress condition, where they had to answer under high time pressure (i.e., 10 s/question) and received either "Correct" or "Incorrect" feedback or to the low stress condition, where they answered identical questions without time pressure or feedback (Fig. 4a–c).

Following the Mental Game, two manipulation checks were included. First, game stressfulness appraisal was measured with 8 items (e.g., difficult, stressful) on a 7-point scale (from "Strongly Disagree" to "Strongly Agree", $\alpha = 0.85$). Second, the participants' state anxiety was measured using the 20-item State anxiety scale of the State-Trait Anxiety Inventory (STAI; Form Y, Spielberger, 2010) on a 4-point scale (from "Almost Never" to "Almost Always", $\alpha = 0.95$).

2.3.3. Results of Study 2

Willingness to get vaccinated **(**Fig. 5**)** Participants considered getting vaccinated against COVID-19 as follows: 130 (28.7%) answered "Definitely Not", 90 (19.9%) answered "Probably Not", 95 (21%) answered "Undecided", 73 (16.1%) answered "Probably Yes", and 65 (14.3%) answered "Definitely Yes".

Manipulation check. The stress manipulation was successful. Participants in the high stress condition ($n = 227$) perceived the Mental Game to be more stressful ($M_{HighStress} = 4.95$, $SD = 1.15$ vs. $M_{LowStress} = 4.23$, $SD = 1.32$, $t\,(451) = -6.13$, $p < 0.01$) than participants in the low stress condition ($n = 226$), and reported higher state anxiety ($M_{HighStress} = 2.12$, $SD = 0.69$ vs. $M_{LowStress} = 1.96$, $SD = 0.66$, $t\,(451) = -2.61$, $p = 0.01$). Furthermore, participants in the high stress condition answered fewer questions correctly than participants in the low stress condition ($M_{HighStress} = 7.00$, $SD = 4.20$ vs. $M_{LowStress} = 12.74$, $SD = 5.77$, $t\,(451) = 12.10$, $p < 0.01$). Fig. 6 depicts mean Stroop RT across various levels of willingness to get vaccinated for participants in the high stress condition as well as the low stress condition.

2.3.3.1. Regression model: the interaction between Stroop RT and stress.

First, we ran Multiple Ordinal Regressions to test the effect of Stroop RT, Stress (low vs. high), and their interactive effect (Stroop × Stress). Next, we introduced all control variables (i.e., demographics, depressed mood, and CRT) in the regression. The dependent variable was willingness to get vaccinated against COVID-19. Stroop RT was the independent variable, Stress was the moderating variable, and all other variables were covariates. For an easier interpretation of the interaction term, we used standardized values for all continuous variables (Table 2).

The results of the analyses lent support to the hypothesized interaction between EF and stress on vaccine hesitancy, estimated the strength of the total effect, and measured its change after controlling for socio-demographic characteristics. Among the demographic covariates, only Black ethnicity (vs. all others), age, and political orientation (Republican vs. Democrat) were statistically significant predictors. Consistent with previous research (Hyland et al., 2021), CRT also had significant associations with willingness to vaccinate. More importantly for our reasoning, as hypothesized, the interaction between Stroop RT and Stress was statistically significant ($B = -0.39$, $SE = 0.18$, OR $= 0.68$, 95% CI from 0.48 to 0.97, $p = 0.03$). One unit of increase in the interaction term (Stroop × Stress) was associated with 0.32 decreased odds of being at a higher level of vaccine acceptance.

To interpret this interaction term, we compared the associations between willingness to get vaccinated and stress, at short (-1SD) and long (+1SD) Stroop RT separately, by using Process Macro (Hayes, 2017). Comparison results indicated that, for participants with a shorter (-1SD) Stroop Reaction Time (i.e., stronger EF), stress had no significant effect on willingness to receive a vaccine ($B = 0.14$, $SE = 0.15$, OR $=$ 1.15, 95% CI from 0.86 to 1.54, $p = 0.36$). For participants with a longer (+1SD) Reaction Time (i.e., weaker EF), however, stress had a significant negative effect on willingness to get vaccinated ($B = -0.33$, $SE =$ 0.16, OR $= 0.72$, 95% CI from 0.52 to 0.99, $p = 0.05$).

Next, we compared the associations between Stroop RT and willingness to get vaccinated for the low stress group and the high stress group, separately. Results indicated that, for the high stress group, the effect of Stroop Reaction Time on willingness to vaccinate was negative and marginally significant ($B = -.13$, $SE = 0.7$, OR $= 0.88$, 95% CI from 0.76 to 1.01, $p = 0.07$). Nonetheless, under low stress, Stroop RT had no significant associations with willingness to receive a vaccine ($B = .13$, $SE = 0.09$, OR $= 1.14$, 95% CI from to 0.95 to 1.38, $p = 0.16$).

Overall, these results were compatible with previous research findings (e.g., Girotti et al., 2018) showing that stress impairs EF, and hence for individuals with weaker EF, stress tends to bring detrimental effects on health-related decisions whereas stronger EF protects individuals from such detrimental effects.

We further examined whether the interaction between Stroop RT and stress had any effects on the attitudinal measurements (e.g., vaccination attitudes, conspiracy beliefs, trust in authorities) included in Supplementary Table S2. Results revealed that trust in authorities was significantly influenced by the interaction between Stroop RT and stress, such that under high stress, longer Stroop RT (i.e., weaker EF) had a negative effect on trust in health authorities. Therefore, Study 2 suggested that trust in authorities was "malleable"(shaped by stress), further shedding light on the underlying mechanism between EF, stress, and willingness to get vaccinated against COVID-19.

On the other hand, COVID-19 conspiracy beliefs were robustly associated with Stroop RT, but neither with stress nor with the interactive effect between stress and Stroop RT, indicating that stress did not lead to significant changes in the link between the participants' Stroop RT and their tendency to endorse COVID-19 conspiracies.

3. General discussion

Addressing vaccine hesitancy continues to be a pressing task for researchers, public health authorities, and policymakers alike. Tackling this major public health problem requires a rigorous understanding of the factors that undermine vaccine acceptance. To this end, we investigated whether executive function (EF) impacts vaccination decisions in the context of the COVID-19 pandemic. Specifically, we first examined the association between EF and vaccine acceptance using cross-sectional

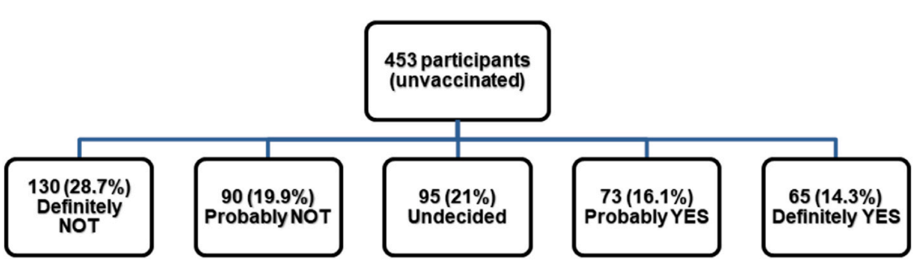


Fig. 5. Response frequencies for willingness to get vaccinated (Study 2).

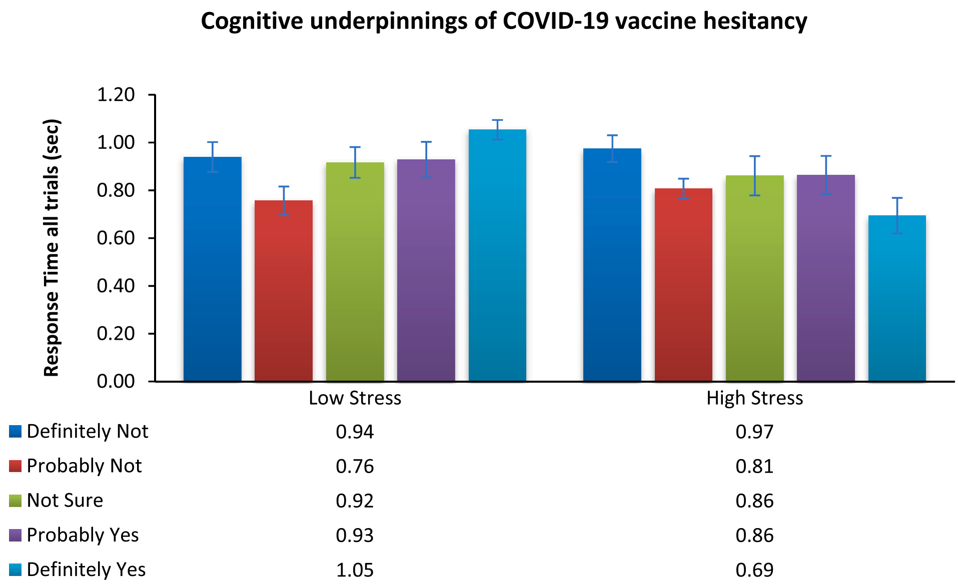


Fig. 6. Mean Stroop Task Reaction Times for different levels of willingness to receive a vaccine against COVID-19 among participants in the Low Stress Group vs. High Stress Group in Study 2 (1 = Definitely Not; 5 = Definitely Yes). Bars represent standard errors.

Table 2
Predicting likelihood of willingness to get vaccinated against COVID-19 in Study 2 as a function of Stroop RT and Stress (N = 453).

	Model 1				Model 2			
Independent Variable	B	SE	OR	95% C.I.	B	SE	OR	95% C.I.
Stroop Performance								
Z(All Trials_RT)	0.12	0.11	–	–	0.19	0.13	–	–
Stress								
Low Stress (0) vs. High Stress (1)	−0.13	0.17	–	–	−0.10	0.17	–	–
Stroop x Stress								
Stress x Z(All Trials_RT)	−0.47 **	0.17	0.63	0.45 to 0.88	−0.39 *	0.18	0.68	0.48 to 0.97
Age								
Z(Age)	–	–	–	–	−0.30 **	0.10	0.74 **	0.61 to 0.89
Gender								
Male (0) vs. Female (1)	–	–	–	–	−0.17	0.19	–	–
Education								
Less than High school	–	–	–	–	1.31	0.99	–	–
High school	–	–	–	–	−0.77 *	0.37	0.46 *	0.22 to 0.96
Some college	–	–	–	–	−0.38	0.33	–	–
College	–	–	–	–	−0.22	0.32	–	–
Some graduate	–	–	–	–	−0.28	0.52	–	–
Graduate degree	–	–	–	–	–	–	–	–
Ethnicity								
White vs. all other	–	–	–	–	−0.42	0.40	–	–
Black vs. all other	–	–	–	–	−1.09 **	0.46	0.34 *	0.14 to 0.82
Asian vs. all other	–	–	–	–	0.27	0.55	–	–
Hispanic vs. all other	–	–	–	–	−0.38	0.46	–	–
Income								
Below 20 K	–	–	–	–	−0.12	0.49	–	–
20 K–39 K	–	–	–	–	−0.03	0.47	–	–
40 K–59 K	–	–	–	–	−0.02	0.50	–	–
60 K–79 K	–	–	–	–	0.22	0.57	–	–
80 K–99 K	–	–	–	–	0.06	0.66	–	–
≥100 K	–	–	–	–	–	–	–	–
Political orientation								
Democrat (1) vs. Republican (0)	–	–	–	–	1.74 **	0.21	5.68 **	3.78 to 8.53
Religiosity								
Z(Religiosity)	–	–	–	–	−0.01	0.10	–	–
Depressed Mood								
Z(PHQ)	–	–	–	–	−0.01	0.10	–	–
Cognitive Reflection								
Z(CRT)	–	–	–	–	0.25**	0.10	1.28	1.06 to 1.54
	$\chi 2$ (3) = 9.32, $p < 0.05$				$\chi 2$ (24) = 126.04, $p < 0.001$			

Note: Multiple variable models using Ordinal Logistic Regressions (OLS) in Study 2, *$p < 0.05$. **$p < 0.01$. All continuous variables are standardized.

data (Study 1), and then we experimentally tested the effect of EF on willingness to get vaccinated against COVID-19 under low vs. high stress (Study 2). The findings of both studies provided support for our hypothesis that executive function predicts COVID-19 vaccine hesitancy. Taken together, our results provide important theoretical implications and research avenues for vaccination stakeholders.

First, our work complements recent research which shows that intuitive (vs. analytical) thinking and lower levels of pre-pandemic cognitive functions correlate positively with vaccine hesitancy (Batty et al., 2021; Martinelli and Veltri, 2021) and that working memory underlies social-distancing compliance during the COVID-19 pandemic (Xie et al., 2020). Critically, our findings show that the unique stepwise contribution of EF to differences in vaccine acceptance cannot be explained by the established socio-demographic factors examined in prior work, such as political orientation, religiosity, education, gender, age, depressed mood, or income. Thus, we document a novel, distinct root of vaccine hesitancy.

Second, understanding the moderating role of stress on the relationship between EF and vaccine acceptance provides implications for health communication. Considering the complexity of vaccine hesitancy, public health practitioners need to be mindful of individual differences in cognitive skills, and disseminate information in a cognitively easy-to-process way that can resonate across the general population. Furthermore, our findings suggest that interventions targeted at boosting immunization need to take into account the rampant levels of psychological stress associated with the COVID-19 pandemic (Langer, 2020). To mitigate the risk of stress-induced decrements in EF, vaccination campaigns can benefit from stress-lowering message framing. Whereas prior vaccination communication has focused primarily on vaccine effectiveness (Dai et al., 2021), the current findings indicate that multiple dimensions should be considered to achieve reassurance and preempt any factors that negatively impact EF. For instance, a promising avenue could be stress reappraisal interventions, which refer to altering how individuals think about an undesirable situation to change the accompanying emotional responses (McRae and Gross, 2020). Recent work shows that such interventions can successfully reduce the undesirable effects of stress on health-related decisions and increase psychological resilience (Wang et al., 2021). On the long run, since stress accelerates cognitive decline and negatively impacts health decision-making (Shields et al., 2016), our work underscores the importance of reducing psychological stress, which in turn lowers threat perceptions and public distrust of healthcare professionals.

Third, the current research corroborates recent work on the role of trust in shaping scientific information and subsequently, vaccination decisions (Hicks, 2022; Latkin et al., 2021; Yuan et al., 2021). Considering the far-reaching implications of public trust, we argue that besides policymakers and governments, other stakeholders need to be concerned, too with fostering trust. For instance, pharmaceutical companies and healthcare providers need to align their recommendations and build coordinated public health narratives in order to avoid undermining trust in science.

3.1. Limitations

While the current inquiry is, to our knowledge, the first to examine the relationship between executive function and vaccination intentions, a number of limitations are worth addressing. First, although we tested our hypotheses across two studies conducted with online convenience samples from the US population, Study 1 relied on cross-sectional data which hindered our ability to draw causal inferences. To address this issue, Study 2 employed an experimental design to examine the causal effect of executive function on vaccination intentions and shed light on the mechanism underlying this relationship. Second, the dependent variable, willingness to receive a COVID-19 vaccine, relied on self-reported intentions rather than observed data. Future studies might address this methodological limitation by recording actual vaccination behavior or employing public health records. Third, willingness to get a COVID-19 vaccine could be categorized in multiple ways. Although we consider our analytic strategy of using ordinal logistic regression to examine various degrees of vaccine hesitancy to be a strength, we are aware that a different categorization of the same variable might yield different results. Similarly, the trimmed data due to excessive time spent on the Stroop Task could be treated differently. We demonstrated that the missing values were distributed randomly yet conservatively opted not to impute or replace them with other values. Nonetheless, we acknowledge that a different treatment of the same variable might lead to different results. Given that the datasets are available online (see Data Availability), researchers interested in the topic are invited to use them to conduct alternative analyses. Finally, it is worth acknowledging that while the MTurk platform has been increasingly used in social science research (Hauser et al., 2021), the current online samples rely on convenience sampling from the US population and are not generalizable worldwide. Considering the worldwide health disparities associated with COVID-19, the current findings should be replicated using nationally representative samples across various populations.

4. Conclusions

Results from two studies conducted with convenience samples of the US population indicate that executive function is associated with vaccination attitudes, COVID-19 conspiracy beliefs, trust in health authorities, and vaccine acceptance. Furthermore, Study 2 demonstrates that the association between executive function and vaccine acceptance is more pronounced under stress. Thus, communication strategies of campaigns advocating for the COVID-19 vaccination need to be sensitive to individuals' executive function skills and their levels of stress. Although further research is needed to fully comprehend the mechanisms underlying vaccine hesitancy, our work reveals that executive function represents a critical driver of vaccination decisions.

By examining vaccination decisions through a psychological lens, our results outline a concerning challenge for the future of immunization against COVID-19. Nevertheless, by uncovering executive function as a novel cognitive root of vaccine hesitancy, our work also provides an opportunity to reduce vaccine hesitancy and ultimately improve public health. Since weaker executive function is associated with multiple negative socio-economic and health-related outcomes (Richland and Burchinal, 2013), from a public policy perspective it might be sensible to target individuals with weaker executive function through communications that employ stress-lowering message framing. Considered jointly, the current results indicate that disseminating health communication in a cognitively accessible manner might be a promising avenue for boosting vaccine acceptance.

Credit author statement

Sinem Acar-Burkay: Conceptualization, Methodology, Software, Validation, Investigation, Data curation, Writing – original draft, Visualization, Funding acquisition. **Daniela-Carmen Cristian**: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft.

Data Availability

Nonidentifiable data from all participants in Study 1 and Study 2 are available in the Open Science Framework data repository at https://osf.io/pve2g/?view_only=6cd16ab52d1c40998c9f2b24eabb7844.

Declaration of competing interest

The authors declare no competing interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.socscimed.2022.114911.

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