SSM - Population Health 15 (2021) 100896

Contents lists available at ScienceDirect

SSM - Population Health

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

Hesitancy in the time of coronavirus: Temporal, spatial, and sociodemographic variations in COVID-19 vaccine hesitancy

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A R T I C L E I N F O

Keywords:
Vaccine hesitancy
COVID-19
Public health
Inequality
Race

A B S T R A C T

Leveraging nationally representative survey data on 443,680 respondents from January to March 2021, this study examines the temporal, spatial, and sociodemographic variations in COVID-19 vaccine hesitancy in the U. S. Findings reveal multidimensional determinants of vaccination intentions involving confidence, complacency, and circumspection factors. Using descriptive analyses and multilevel mixed-effects regression models, we find persistent partisan divide across states and significant racial disparities, with Blacks more likely to develop vaccine hesitancy due to confidence and circumspection than Whites. Vaccine hesitancy among Blacks declines dramatically across time but varies little across states, indicating new directions to effectively address inequalities in vaccination. Results also show nuanced gender differences, with women more likely to develop hesitancy due to circumspection and men more likely to have hesitancy due to complacency. Moreover, we find important intersection between race, gender, and education that calls for efforts to adequately address the concerns of the most vulnerable and disadvantaged groups.

1. Introduction

The COVID-19 pandemic might be unprecedented, but the vaccine hesitancy associated with it is nothing new. Defined by the World Health Organization (WHO) as the "delay in acceptance or refusal of vaccination despite availability of vaccination services" (MacDonald & SAGE Working Group on Vaccine Hesitancy, 2015), vaccine hesitancy has been reported in more than 90% of countries worldwide and has been increasing globally in the past few years, leading to a subsequent decrease in vaccination rates and an increase in outbreaks of vaccine-preventable diseases (de Figueiredo et al., 2020; Lane et al., 2018). Recent polls found that around 25%–35% of the U.S. population reported that they would not uptake a COVID-19 vaccine (e.g., Agiesta, 2021; Brumfiel, 2021; Funk & Tyson, 2021; Saad, 2021).

At the same time, we have long known that vaccination is not only a health issue but also involves the interaction of social, cultural, and political forces. Vaccination rates have been constantly low among minority and disadvantaged groups (Quinn et al., 2016; Wang, Munshi, and Hong 2014), and vaccination is often a topic of heated debate in American partisan politics (Baum, 2011; Dann, 2015). Vaccine hesitancy, in particular, stems from a complex decision-making process that involves emotional, cultural, social, political, and cognitive factors, and there is simply no cure-all solution (Dubé et al., 2015). To understand what factors might have contributed to the development of vaccine hesitancy and what efforts and structural changes should be made to reduce hesitancy and improve vaccination rates, it then becomes crucial to examine how vaccine hesitancy is manifested across different sociodemographic groups and local political contexts.

Despite recent efforts to examine the extent and patterns of COVID-19 vaccine hesitancy (e.g., Callaghan et al., 2021; Latkin et al., 2021; Murphy et al., 2021; Nguyen et al., 2021; Savoia et al., 2021), there has yet to be a study examining the potential intersection in vaccine hesitancy across different sociodemographic characteristics, such as gender, race, and education, and diving into the varying patterns of sociodemographic stratification across time and different local political contexts. Utilizing the most recent nationally representative data from the Household Pulse Survey (HPS) implemented by the U.S. Census Bureau, we examine the temporal, spatial, and sociodemographic variation of vaccine hesitancy during the COVID-19 pandemic. We aim to answer the following research questions: 1) How does COVID-19 vaccine hesitancy, measured in different dimensions of determinants, vary across sociodemographic groups? 2) How does COVID-19 vaccine

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https://doi.org/10.1016/j.ssmph.2021.100896
Received 26 May 2021; Received in revised form 13 July 2021; Accepted 11 August 2021
Available online 13 August 2021

Table 1
Unweighted overall descriptive statistics.

Variable	N = 443,680[1]
Vaccine Hesitancy	
Overall Hesitancy	59,893 (13%)
Hesitancy Due to Confidence	29,168 (6.6%)
Hesitancy Due to Circumspection	44,806 (10.0%)
Hesitancy Due to Complacency	11,351 (2.6%)
Gender	
Female	265,359 (60%)
Male	178,321 (40%)
Race	
White	332,449 (75%)
Asian	20,956 (4.7%)
Black	31,944 (7.2%)
Hispanic	42,830 (9.7%)
Other/Mixed	15,501 (3.5%)
Education	
Less than High School	9582 (2.2%)
High School	51,287 (12%)
Associate or Some College	143,655 (32%)
Bachelor	128,062 (29%)
Graduate	111,094 (25%)
Age	53.92 (15.94)
Married	261,712 (59%)
Number of Household Adults	2.13 (0.96)
Number of Household Children	0.61 (1.02)
Had COVID	49,824 (11%)
Week	
22	66,562 (15%)
23	78,251 (18%)
24	74,586 (17%)
25	75,106 (17%)
26	75,335 (17%)
27	73,840 (17%)

2. Vaccine hesitancy: determinants and disparities

2.1. Vaccine hesitancy: A multidimensional construct

This study adopts the official definition of vaccine hesitancy from WHO (MacDonald & SAGE Working Group on Vaccine Hesitancy, 2015), but it is worth pointing out that vaccine hesitancy is a highly complex and multi-dimensional concept that may not be measured in the same way across different studies (Dubé et al., 2013). Research shows that vaccine hesitancy should be understood in a broader socio-cultural context and can be influenced by a wide range of factors, including but not limited to: trust in modern science, mainstream medicine, health authorities, large corporations, and government (e.g., Hornsey et al., 2020; Larson et al., 2013; Siddiqui et al., 2013; Yaqub et al., 2014); concerns about side-risks or other perceived risks, and the preference for "natural risks" over "manmade risks" (Ball et al., 1998; Serpell & Green, 2006); access to health information through health professionals and social networks (Ahmed et al., 2018; Yaqub et al., 2014); misinformation and misperceptions (Siddiqui et al., 2013); "local vaccination cultures" that characterize shared local beliefs, views, and vaccination settings (Streefland et al., 1999); past experiences with vaccination (Busse et al., 2011); philosophical, moral, or religious convictions (Ruijs et al., 2012; Streefland, 2001).[1]

To better understand the multidimensional nature of vaccine hesitancy, the WHO Strategic Advisory Group of Experts (SAGE) Working Group on Vaccine Hesitancy recommends a "3Cs" model, which highlights three intersecting categories of determinants: *Confidence*, *Complacency*, and *Convenience*. Confidence includes trust in the effectiveness and safety of the vaccines, the reliability and competence of the system that delivers them, and the motivations of policymakers. Complacency exists when perceived risks of vaccine-preventable diseases are low, and vaccination is perceived as an unnecessary action. Convenience covers factors like physical availability, affordability, and accessibility of vaccines; it is also relevant to whether the vaccination services are delivered in a convenient and comfortable way based on the time, location, and cultural context.

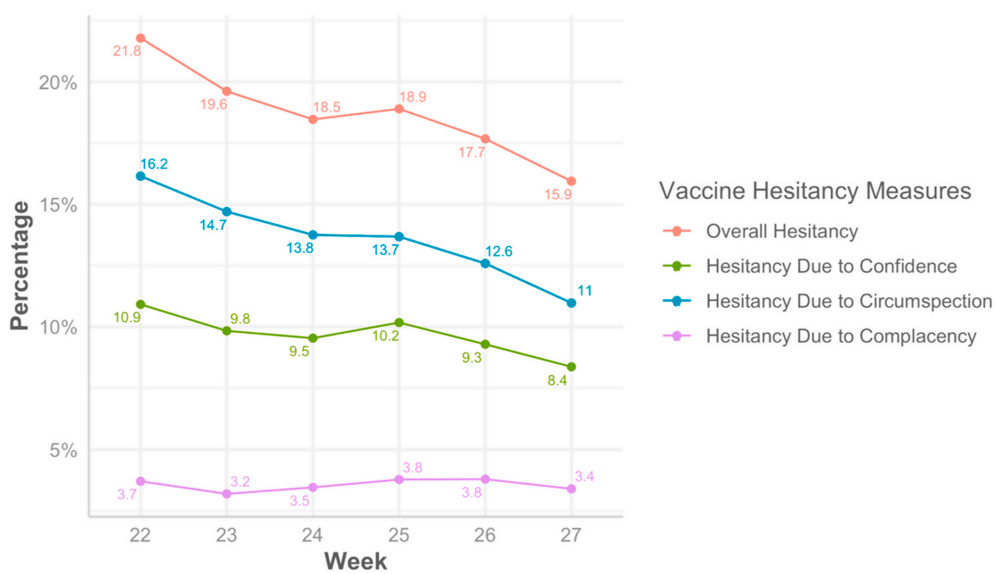

Fig. 1. Vaccine hesitancy trend, overall.

hesitancy change at different rates across sociodemographic groups? 3) How are disparities in COVID-19 vaccine hesitancy across sociodemographic groups associated with state-level political environment? 4) How do different sociodemographic characteristics such as race, gender, and class intersect to affect COVID-19 vaccine hesitancy?

[1] For more detailed reviews on the determinants of vaccine hesitancy, please see Dubé et al. (2013), Larson et al. (2014), Yaqub et al. (2014), and Salmon et al. (2015).

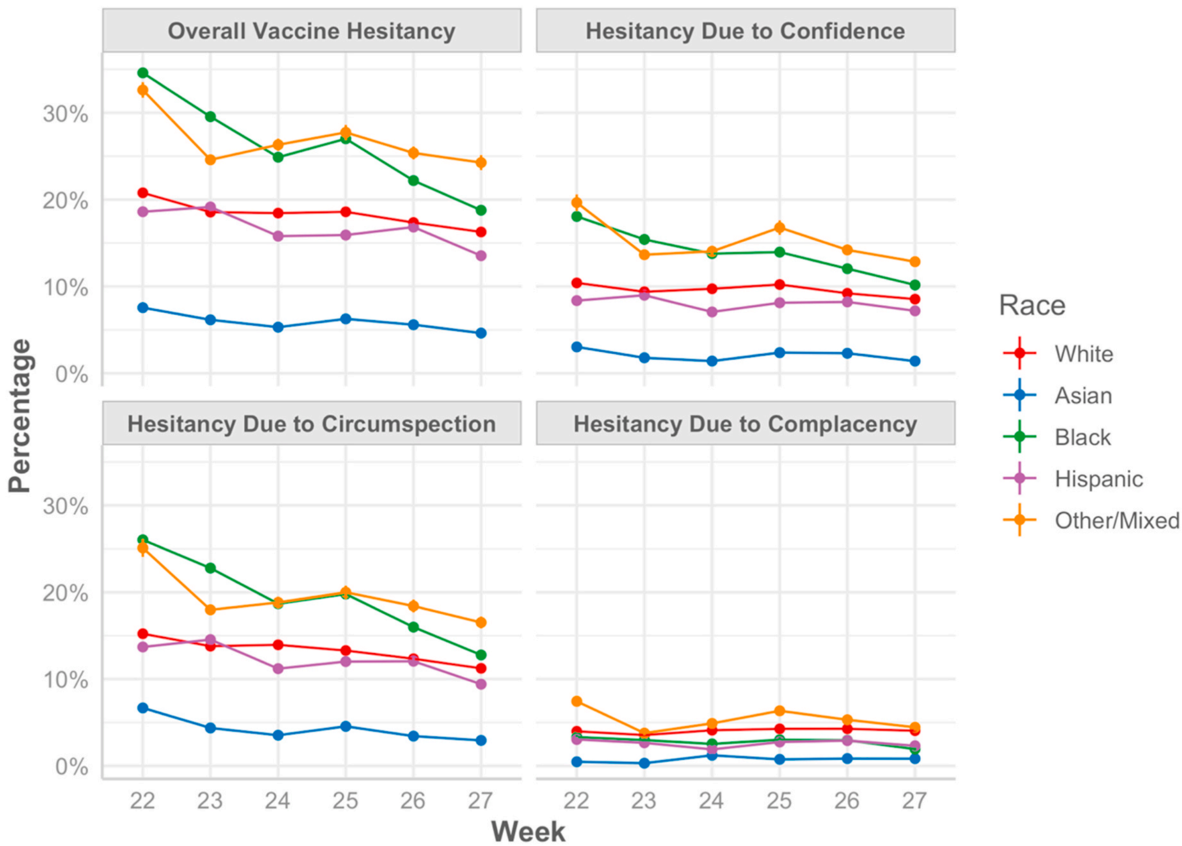

Fig. 2. Vaccine hesitancy trend by race.

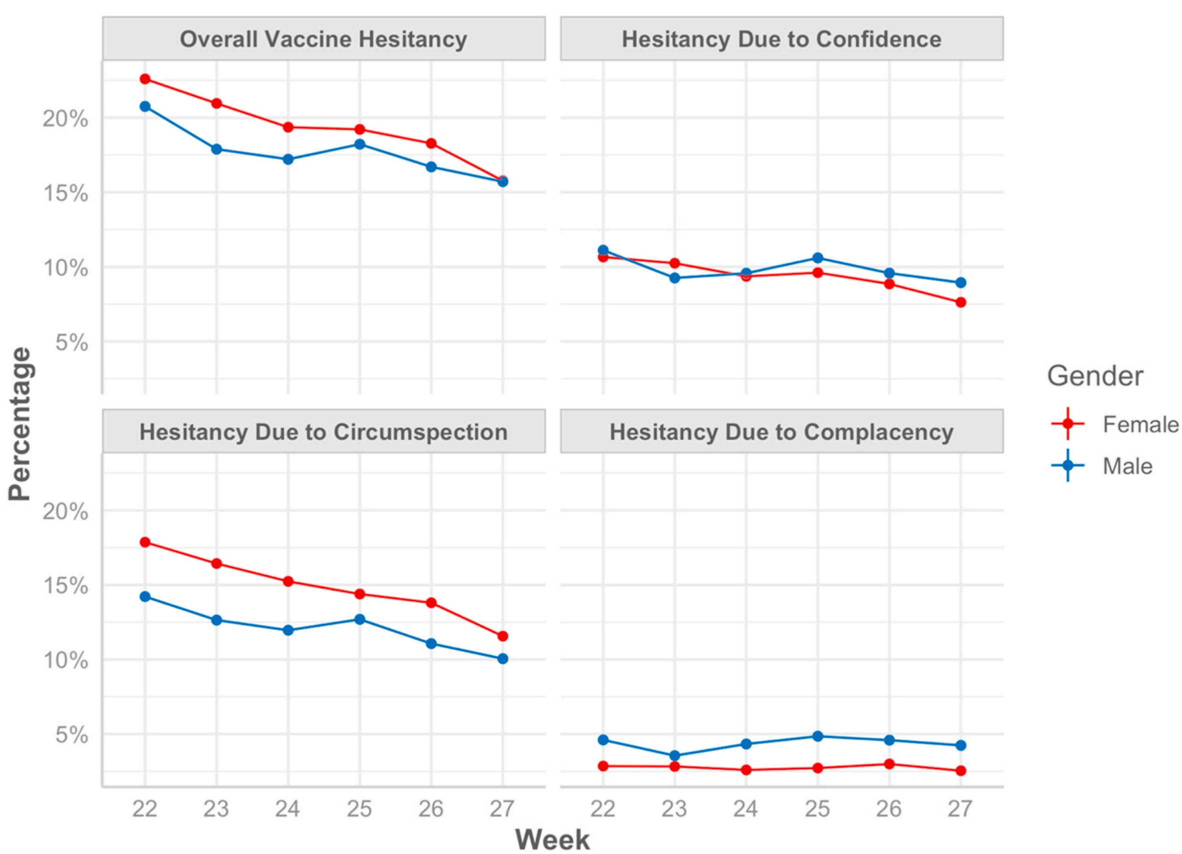

Fig. 3. Vaccine hesitancy trend by gender.

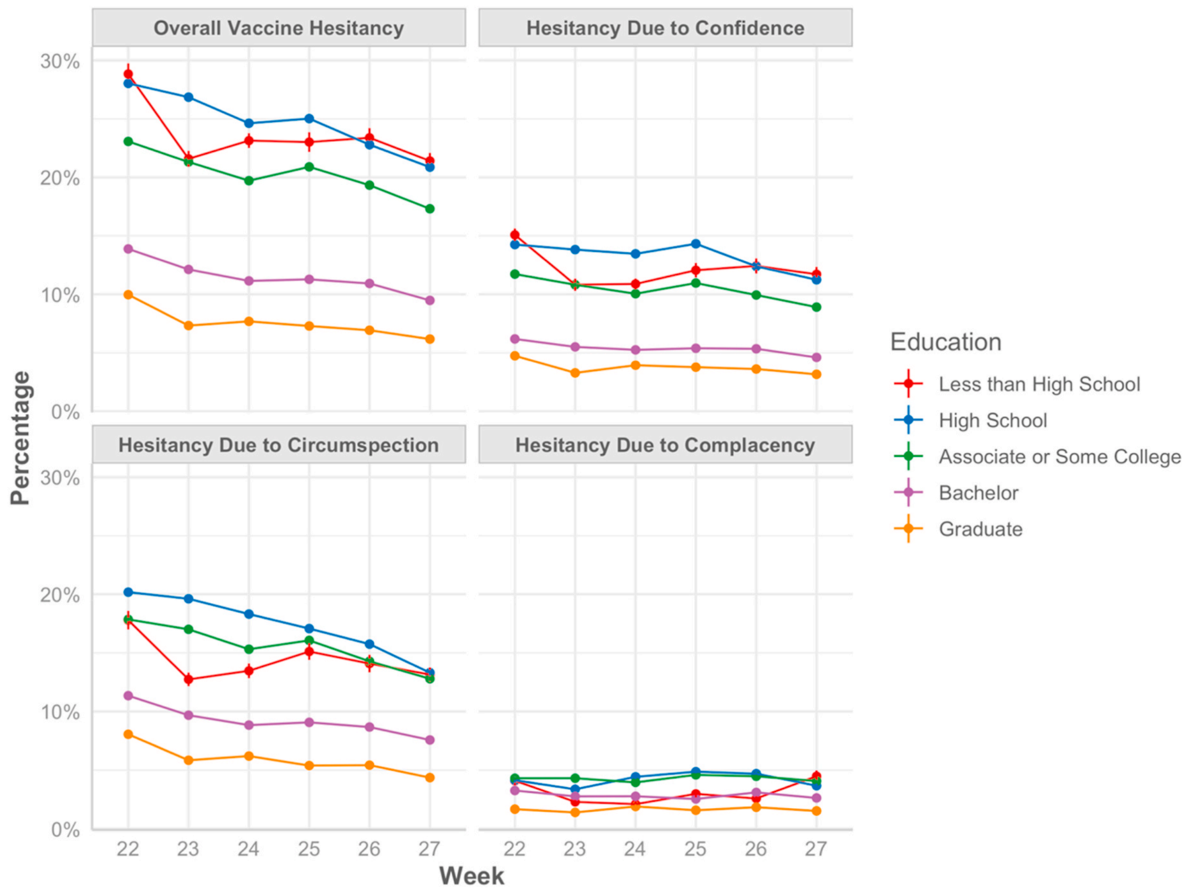

Fig. 4. Vaccine hesitancy trend by education.

However, some scholars argue that vaccine hesitancy could have more complex dimensions emerging from understandings of risk and science in post-modern societies (Dubé et al., 2013; Vulpe, 2020). Moreover, vaccine hesitancy is context-specific and can vary across time, place, and vaccines (Larson et al., 2014). Individuals with vaccine hesitancy may accept some vaccines but reject others, delay vaccine but ultimately receive it for themselves or their children, and develop hesitancy for highly variable reasons in different societies and contexts (Falagas & Zarkadoulia, 2008; Larson et al., 2015; Rainey et al., 2011). To develop more effective strategies addressing vaccine hesitancy for a particular vaccine-preventable disease, it is thus crucial to examine the specific social and political context, to measure vaccine hesitancy as a multidimensional construct, and to examine the variations and changes of each dimension across different sociodemographic groups.

2.2. *Sociodemographic stratification of vaccine attitudes*

Persistent disparities in vaccine behaviors and attitudes have been found across sociodemographic groups. For example, people with lower socioeconomic status are generally less likely to be vaccinated or vaccinate their children and more likely to have vaccine hesitancy (Bocquier et al., 2017; Hinman & McKinlay, 2015; Murphy et al., 2021; Wagner et al., 2019). Some studies show that men are more likely to receive vaccination than women (Flanagan et al., 2017; Pulcini et al., 2013). When it comes to the impact of education, studies tend to focus on parental vaccination decisions for their children and the evidence is mixed: while some studies find that education is positively associated with vaccination of one's children (e.g., Gust et al., 2005; Kim et al., 2007; Prislin et al., 1998), others show no significant association between education and vaccine hesitancy (Wagner et al., 2019). Some evidence even shows that highly educated parents are more likely to delay or refuse vaccination for their children and have more concerns over vaccines (e.g., Facciolà et al., 2019; Opel et al., 2011; Smith et al., 2004). This further indicates that vaccine hesitancy is not only about lack of knowledge, information, or access, but may involve a more active calculation and decision process.

Furthermore, evidence shows concerning racial disparities in vaccination. In particular, studies in the U.S. show that Blacks are less likely to receive vaccinations than Whites (Quinn et al., 2017; Wang et al., 2014). While part of this disparity can be explained by differential access to health care systems and vaccination opportunities (Logan, 2009), evidence indicates that vaccine attitudes, such as concerns about vaccine safety, effectiveness, and necessity, also play an important role (Ojha et al., 2015). In particular, the historical and persistent systemic racism in the U.S. may lead to lower levels of trust towards government and authorities among the Black community, which can further lead to racial disparities in vaccination (Quinn et al., 2016). It has been found that racial discrimination and racial fairness in a health care setting could impact racial disparities in vaccine uptake through affecting vaccine attitudes: while racial discrimination increases perceived vaccine risk among Blacks, racial fairness increases their trust and decreases perceived vaccine risks (Quinn et al., 2017).

Recent studies and opinion polls reveal some evidence on sociodemographic disparities in COVID-19 vaccine attitudes and uptake. For example, a survey given to a national sample from May 28 to June 8, 2020 shows that intention to refuse vaccination is highest for women and Blacks (Callaghan et al., 2021). A poll conducted during February 16–21, 2021 by the Pew Research Center shows that people with lower income levels tend to be less inclined to get a vaccine than those with higher incomes, and women are less likely than men to intend to get a vaccine or have already received at least one dose (Funk & Tyson, 2021). A Gallup Panel Survey conducted from December 2020 to January 2021

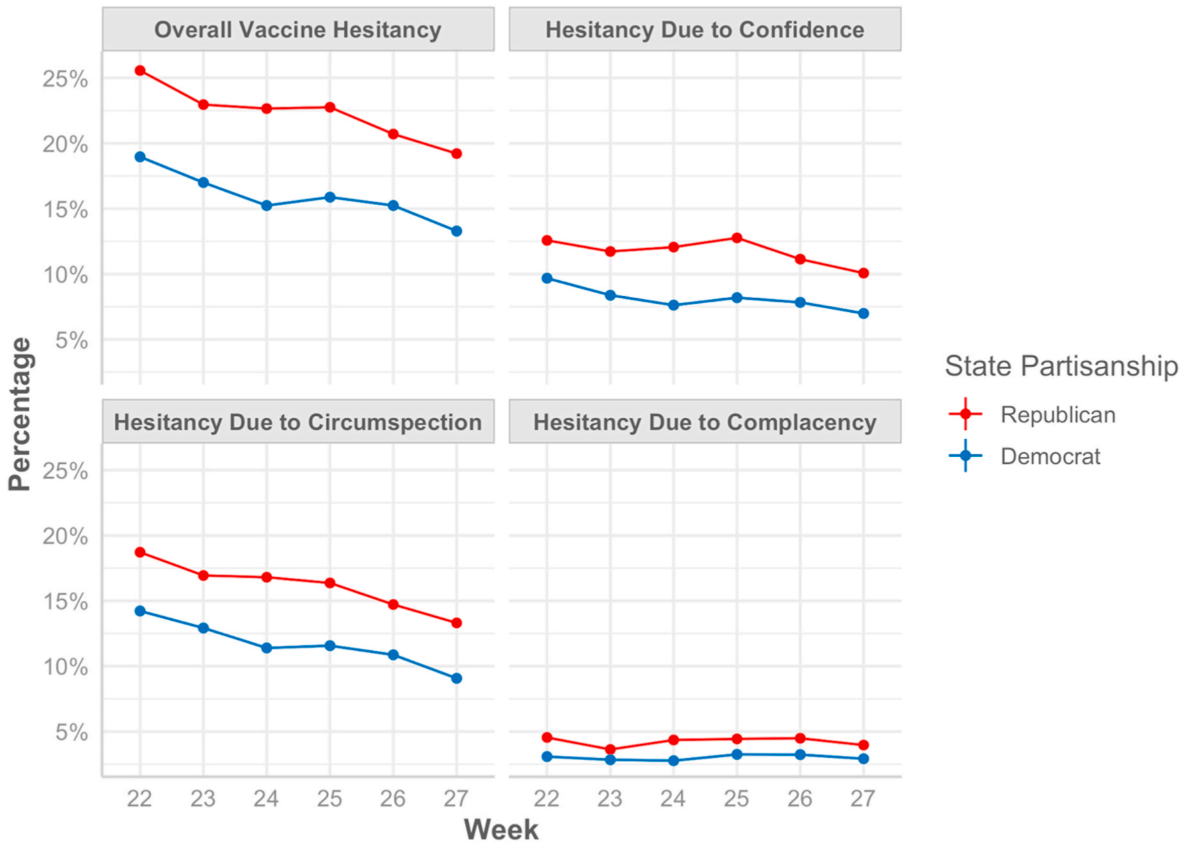

Fig. 5. Vaccine hesitancy trend by state partisanship.

shows that non-White adults are less inclined to be vaccinated than Whites, and four-year college graduates are more inclined to be vaccinated than those without a college degree (Saad, 2021). Another survey conducted in December 2020 showed similar racial disparities, and in particular revealed that past experience of racial discrimination plays an important role in producing racial differences in attitudes towards COVID-19 vaccines (Savoia et al., 2021). On the other hand, while the Institute for Health Metrics and Evaluation (2021) recently published an online interactive map showing the temporal and spatial variation of COVID-19 vaccine hesitancy across U.S. counties, this map does not present the socioeconomic disparities. Therefore, there has yet to be a study examining the sociodemographic variation of vaccine hesitancy across time and space, and investigating potential intersectionality between race, gender, and education.

2.3. Partisan differences in vaccine attitudes

In addition to the individual-level attributes that might affect the level of people's vaccine hesitancy, political influences are also unneglectable forces shaping public attitudes toward the COVID-19 vaccine. Past polls and studies have documented that Republicans, compared to their Democratic counterparts, were more likely to believe that the alleged vaccine-autism link is true (Lupton & Hare, 2015), less likely to support required childhood vaccinations (Anderson, 2015), and less willing to take the influenza vaccine (Baum, 2011; Mesch & Schwirian, 2015). Adolescent vaccination coverage was consistently lower in red states than in blue states for human papillomavirus (HPV), tetanus-containing (Tdap), and meningococcal (MCV4) vaccines (Bernstein et al., 2016).

The partisan divide only becomes fiercer and sometimes irreconcilable in the COVID-19 pandemic. In terms of governing and administration, the responses to the pandemic are drastically different between Republican and Democratic governments at the federal, state and local levels (Chen & Karim, 2021). In terms of public attitudes and behaviors, geo-tracking data of over 15 million smartphones per day revealed that Republican counties exhibited 14% less physical distancing than Democratic counties (Gollwitzer et al., 2020). As of April 27, 2021, actual vaccination data showed that the vaccination rates are far higher among counties that voted for Biden than those voted for Trump in the 2020 presidential election (Bump, 2021).

After the U.S. Food and Drug Administration (FDA) granted Emergency Use Authorization to multiple COVID-19 vaccines and the launch of massive vaccination programs, we expect that in general, state-level vaccine hesitancy will be associated with state partisanship such that Republican states will demonstrate greater vaccine hesitancy than Democratic states. We will further examine whether state partisanship moderates the impact of individual-level attributes on vaccine hesitancy as discussed in the previous section. Results could point to more targeted initiatives to improve vaccination in accordance with local contexts.

3. Data and methods

3.1. Data

Our primary data source is the public microdata of the HPS conducted by the U.S. Census Bureau in collaboration with multiple federal agencies. The HPS is a new survey project launched in April 2020 with a special aim to shed light on the social and economic impact of the COVID-19 pandemic. Based on national household probability samples, this weekly short survey provides a near real-time snapshot of people's experiences during the pandemic by asking questions related to

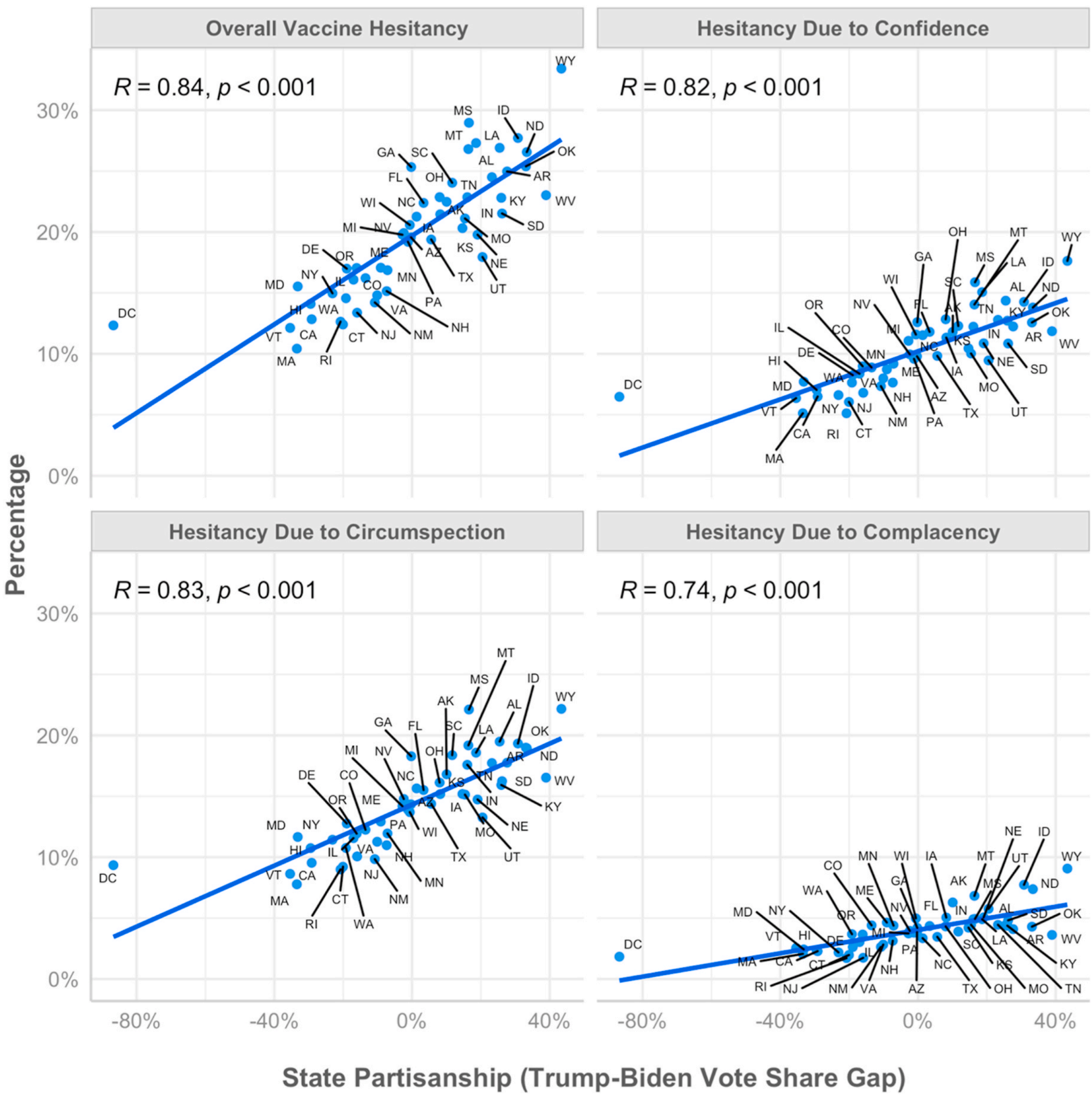

Fig. 6. Scatterplot of state-level vaccine hesitancy and state partisanship.

employment status, food security, housing, physical and mental health, access to unemployment insurance and health care, education disruptions, and so on. Starting from week 22[2] of the HPS data collection period, new questions regarding vaccine attitudes were added to the questionnaire. We thus use data from week 22 (January 6–18, 2021) to week 27 (March 17–29, 2021), the most recent week with available data when this manuscript was written, to conduct the analyses for this study.

The HPS is designed to produce state-level estimates for each of the 50 states plus the District of Columbia. For each data collection period from week 22–27, independent samples of households were selected, and each sampled household was interviewed once. The average number of valid respondents in each collection period is around 76,540, resulting in 459,235 respondents across these six periods.[3] We further remove 3% of cases that have missing data in the main outcome variables and covariates, resulting in 443,680 cases.

3.2. Variables

3.2.1. Outcome variables

To capture the multidimensional nature of vaccine hesitancy and distinguish between its various determinants, we constructed four measures on vaccine hesitancy. The HPS first asked respondents whether they had received a COVID-19 vaccine or not. If a respondent has received a COVID-19 vaccine, the HPS followed up with a second question “Did you receive (or do you plan to receive) all required doses?” (1 = Yes, 2 = No). If a respondent has not received a COVID-19 vaccine or has not received (or does not plan to receive) all required doses, the HPS asked a third question about their intention to get a

[2] Phase 1 of the HPS survey was conducted weekly from April 23 to July 21, 2020. Starting from Phase 2, the HPS survey was conducted biweekly over a 13-day period. The HPS technical documents continue to count these collection periods as “weeks” for continuity with Phase 1. For details of the start and end dates of each data collection period, please refer to the HPS Technical Documentations at https://www.census.gov/programs-surveys/household-pulse-survey/technical-documentation.html.

[3] Details about state-level sample sizes and number of responses can be found in the State-level Quality Measures spreadsheet at https://www.census.gov/programs-surveys/household-pulse-survey/technicaldocumentation.html.

Table 2
Multilevel models predicting vaccine hesitancy.

Predictor	Overall	Confidence	Circumspection	Complacency
	(1)	(2)	(3)	(4)
Male	−0.13°*** (0.01)	0.05 *** (0.01)	−0.22 *** (0.01)	0.46 *** (0.02)
Race (Reference = White)				
Asian	−0.93 *** (0.03)	−1.10 *** (0.05)	−0.88 *** (0.04)	−1.39 *** (0.08)
Black	0.33 *** (0.02)	0.32 *** (0.02)	0.35 *** (0.02)	−0.38 *** (0.04)
Hispanic	−0.29 *** (0.02)	−0.31 *** (0.02)	−0.25 *** (0.02)	−0.55 *** (0.04)
Other/Mixed	0.29 *** (0.02)	0.35 *** (0.03)	0.26 *** (0.02)	0.12 ** (0.04)
Education (Reference = Less Than High School)				
High School	0.12 *** (0.03)	0.11 ** (0.04)	0.29 *** (0.03)	0.37 *** (0.06)
Associate or Some College	−0.19 *** (0.03)	−0.19 *** (0.03)	0.06 (0.03)	0.24 *** (0.06)
Bachelor	−0.84 *** (0.03)	−0.83 *** (0.04)	−0.51 *** (0.03)	−0.13 * (0.06)
Graduate	−1.28 *** (0.03)	−1.25 *** (0.04)	−0.97 *** (0.03)	−0.59 *** (0.07)
Age	−0.03 *** (0.00)	−0.03 *** (0.00)	−0.03 *** (0.00)	−0.04 *** (0.00)
Married	−0.16 *** (0.01)	−0.17 *** (0.01)	−0.11 *** (0.01)	0.03 (0.02)
Household Number of Children	0.23 *** (0.00)	0.21 *** (0.01)	0.21 *** (0.00)	0.22 *** (0.01)
Household Number of Adults	0.03 *** (0.00)	0.03 *** (0.01)	0.02 ** (0.01)	0.02 * (0.01)
Had COVID	0.26 *** (0.01)	0.04 * (0.02)	0.20 *** (0.01)	−0.05 (0.03)
HDI	−2.02 (1.18)	−1.92 (1.24)	−1.56 (1.02)	0.81 (1.72)
Percentage of White Population	−0.44 * (0.18)	−0.43 * (0.19)	−0.51 ** (0.16)	−0.14 (0.27)
State Partisanship	1.08 *** (0.12)	1.00 *** (0.13)	1.01 *** (0.11)	1.09 *** (0.18)
Data Collection Period (Week)	−0.07 *** (0.00)	−0.04 *** (0.00)	−0.08 *** (0.00)	0.01 (0.01)
Marginal R^2	0.192	0.180	0.186	0.211
Conditional R^2	0.197	0.185	0.189	0.220

Note: *p < 0.05 **p < 0.01 ***p < 0.001. N = 443,680. Standard errors in parentheses. Multilevel mixed-effects logistic regression models with state-level random intercepts effects. Showing log-odds estimation. Each column is a separate model predicting different vaccine hesitancy measures. State partisanship is defined as the state Trump-Biden vote share gap in the 2020 presidential election; a higher value indicates the state leans more towards Republican.

vaccine once it becomes available (1 = Definitely get a vaccine; 2 = Probably get a vaccine; 3 = Probably NOT get a vaccine; 4 = Definitely NOT get a vaccine). We first use all three questions to construct a binary indicator for *Overall Vaccine Hesitancy (OVH)*. Consistent with the most recent report on COVID-19 vaccine hesitancy from the Office of the Assistant Secretary for Planning and Evaluation (2021), we define OVH = 1 if a respondent indicates that they would "probably not" or "definitely not" receive a COVID-19 vaccine when available. We then combine those who already received all required doses, who plan to receive all required doses, and those who had not received a COVID-19 vaccine but would definitely or probably get one once it becomes available. We define this group as OVH = 0, or not having vaccine hesitancy.

Table 3
Multilevel models predicting vaccine hesitancy with interaction terms between week and demographic variables.

	Overall	Confidence	Circumspection	Complacency
	(1)	(2)	(3)	(4)
Panel A: Week X Race (Reference = White)				
Week	−0.05 *** (0.00)	−0.02 *** (0.00)	−0.06 *** (0.00)	0.01 (0.01)
Week X Asian	−0.03 (0.02)	−0.02 (0.03)	−0.05 * (0.02)	0.08 (0.05)
Week X Black	−0.14 *** (0.01)	−0.13 *** (0.01)	−0.13 *** (0.01)	−0.07 ** (0.02)
Week X Hispanic	−0.04 *** (0.01)	−0.03 ** (0.01)	−0.05 *** (0.01)	−0.01 (0.02)
Week X Other/Mixed	−0.01 (0.01)	−0.03 (0.02)	−0.01 (0.01)	−0.01 (0.02)
Panel B: Week X Education (Reference = Less Than High School)				
Week	−0.05 ** (0.01)	−0.02 (0.02)	−0.05 ** (0.02)	0.03 (0.03)
Week X High School	−0.02 (0.02)	−0.01 (0.02)	−0.04 (0.02)	−0.01 (0.04)
Week X Associate or Some College	−0.02 (0.02)	−0.01 (0.02)	−0.02 (0.02)	−0.02 (0.04)
Week X Bachelor	−0.02 (0.02)	−0.01 (0.02)	−0.02 (0.02)	−0.02 (0.04)
Week X Graduate	−0.03 * (0.02)	−0.03 (0.02)	−0.05 * (0.02)	−0.04 (0.04)
Panel C: Week X Gender				
Week	−0.08 *** (0.00)	−0.05 *** (0.00)	−0.09 *** (0.00)	0.00 (0.01)
Week X Male	0.03 *** (0.01)	0.03 *** (0.01)	0.03 *** (0.01)	0.00 (0.01)

Note: *p < 0.05 **p < 0.01 ***p < 0.001. N = 443,680. Standard errors in parentheses. Multilevel logistic regression models with state-level random intercepts effects. Showing log-odds estimation. Each panel is a separate set of models with an interaction term between the data collection period (week) and the corresponding sociodemographic variable (race, education, or gender) added to the base models shown in Table 2. All control variables at the individual and state levels are included in the models but omitted from the table. The main effects of the sociodemographic variables in the interaction terms are also included in the models but omitted from the table. The main effects of Week show the changes in the log-odds of vaccine hesitancy in the reference group between two adjacent data collection periods. The interaction effects show the differences in the changes in the log-odds of vaccine hesitancy between two adjacent data collection periods in the reference group and the focus group.

For those who chose 2, 3, or 4 when answering the vaccine intention question, the HPS further asked about the reasons for their vaccine hesitancy. Eleven options were provided: a1) I am concerned about possible side effects of a COVID-19 vaccine; a2) I don't know if a COVID-19 vaccine will work; a3) I don't believe I need a COVID-19 vaccine; a4) I don't like vaccines; a5) My doctor has not recommended it; a6) I plan to wait and see if it is safe and may get it later; a7) I think other people need it more than I do right now; a8) I am concerned about the cost of a COVID-19 vaccine; a9) I don't trust COVID-19 vaccines; a10) I don't trust the government; and a11) Other. Respondents were asked to "select all that apply". For those who selected answer option 3, the HPS followed up with an additional question on why they believed that they didn't need a COVID-19 vaccine. Six answer options were provided: b1) I already had COVID-19; b2) I am not a member of a high-risk group; b3) I plan to use masks or other precautions instead; b4) I don't believe COVID-19 is a serious illness; b5) I don't think vaccines are beneficial; and b6) Other. Respondents were again asked to "select all that apply".

Based on previous literature and results from exploratory factor analysis, we adapt the WHO "3Cs" model and define a new 3Cs model of vaccine hesitancy that includes three dimensions: *Confidence*,

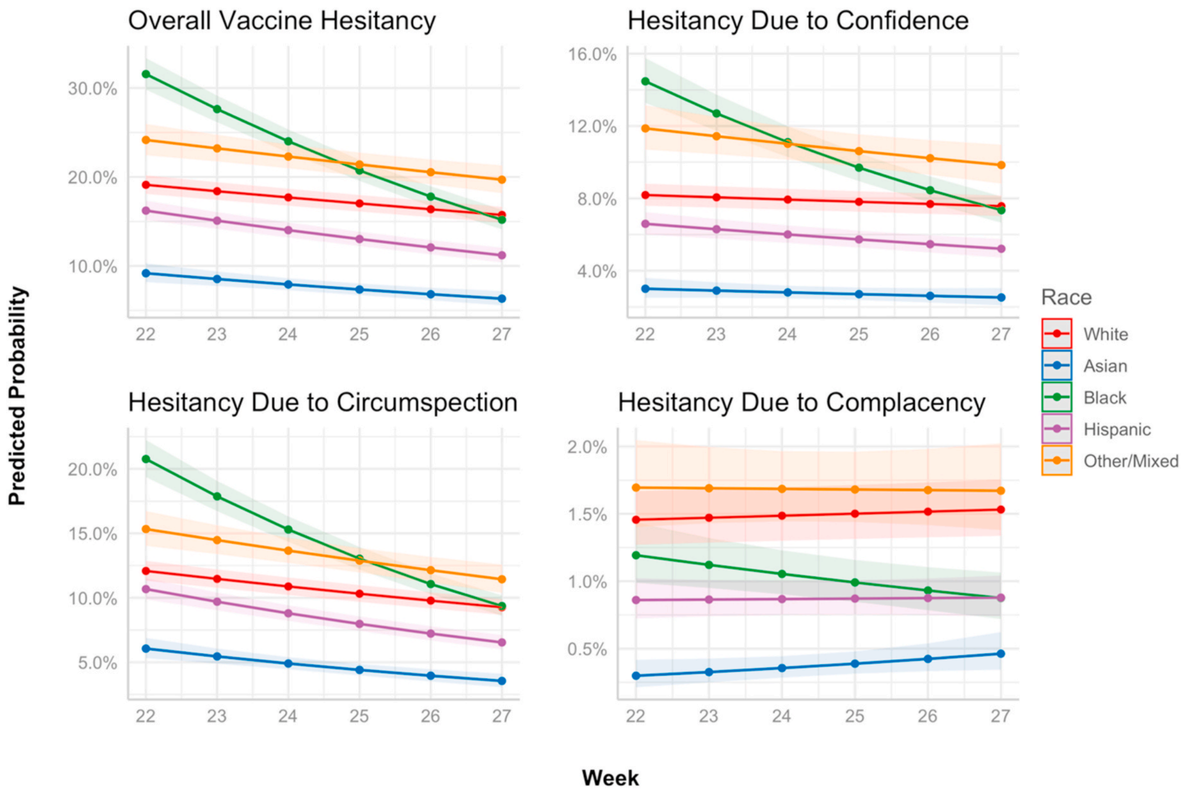

Fig. 7. Predicted probability of vaccine hesitancy by week and race. Note: Figure based on panel A in Table 3. Showing predicted probabilities and 95% confidence intervals.

Complacency, and Circumspection.[4] Same as the WHO 3Cs model, *confidence* is defined as trust in the effectiveness and safety of vaccines as well as the system that delivers them; it covers options a4, a9, a10, and b5. *Complacency* is defined as the perceived risks of vaccine-preventable diseases and thus the necessity of a particular vaccine; it covers options b2, b3, and b4. The new dimension, *circumspection,* is defined as the weighting of benefits and costs of taking a particular vaccine based on evolving information. It is thus broader than the *convenience* dimension in the WHO 3Cs model as it covers not only the accessibility and affordability of a vaccine but also considers the real-time information on its benefits and costs for a particular individual. The resulting *Circumspection* measure covers answer options a1, a2, a6, a7, and a8.[5] For details of the factor analysis results to support these constructed measures, please see Appendices 1-3.[6]

Based on the new 3Cs model, we construct three binary vaccine hesitancy measures: hesitancy due to confidence, circumspection, and complacency. If a respondent selected any one option under each category, the corresponding measure will be coded as 1, otherwise 0. We construct these measures as binary indicators for two reasons. First, the binary measures are more interpretable than continuous indices as we can estimate the percentage of people with vaccine hesitancy under each category in each state and across different demographic groups. Second, the two questions regarding reasons for vaccine hesitancy have a nested structure, and respondents who did not select option a3 were not exposed to options b1-b6; it would thus be inappropriate to construct continuous, additive measures on the intensity of each type of vaccine hesitancy.

3.2.2. *Individual-level covariates*

We categorize respondent *Race/Ethnicity* into five groups: Non-Hispanic White, Non-Hispanic Black, Non-Hispanic Asian, Hispanic, and Mixed/Other. We measure respondent *Highest Education Attainment* in five levels: less than high school, high school graduate or equivalent, some college or associate degree, bachelor's degree, or graduate degree. We further control for respondent gender, age, marital status (1 = Now Married, 0 = Widowed, divorced, separated, or never married), total number of adults in household, total number of children under 18-years-old in household, and whether the respondent had been told by a doctor or other health care provider that they had COVID-19 (1 = Yes, 0 = No). For descriptive statistics of all individual-level variables, please see Table 1.

3.3. *State-level covariates*

To measure state-level political context, we construct an index on *state partisanship* using the method in Gollwitzer et al. (2020). This is a continuous index measuring state-level voting gap in the 2020 presidential election by subtracting the state percentage of total votes for Joseph Biden from the state percentage of total votes for Donald Trump.

[4] While vaccine hesitancy is a highly complex, multidimensional construct and scholars debate on the best ways to categorize various factors contributing to it, we adopted a data-driven approach with exploratory factor analysis to cluster these HPS answer options. First, the Scree Test results based on the Kaiser rule (Kaiser, 1960), the Cattell's scree test (Cattell, 1966), and the parallel analysis (Horn, 1965) all suggest that we should extract three underlying factors out of all answer options. We then conducted exploratory factor analysis to extract three factors and grouped each answer option to the factor in which it has the highest loading. We show the scree plot, the factor loading table, and the correlation matrix between the three factors in Appendices 1-3.

[5] We do not include a5 in these measures because doctors' recommendation may be based on a respondent's specific medical conditions that cannot be altered. We do not include b1 in these measures because the history of COVID-19 infection could bring confounding factors into the analyses. Instead, we include another direct question on whether or not a doctor or provider has told the respondent that they had COVID-19 as a control variable.

[6] Anonymous Reviewer 3 suggested that we conduct analyses separately for a4, a5, and a8. We included these analyses in Appendices 11-14.

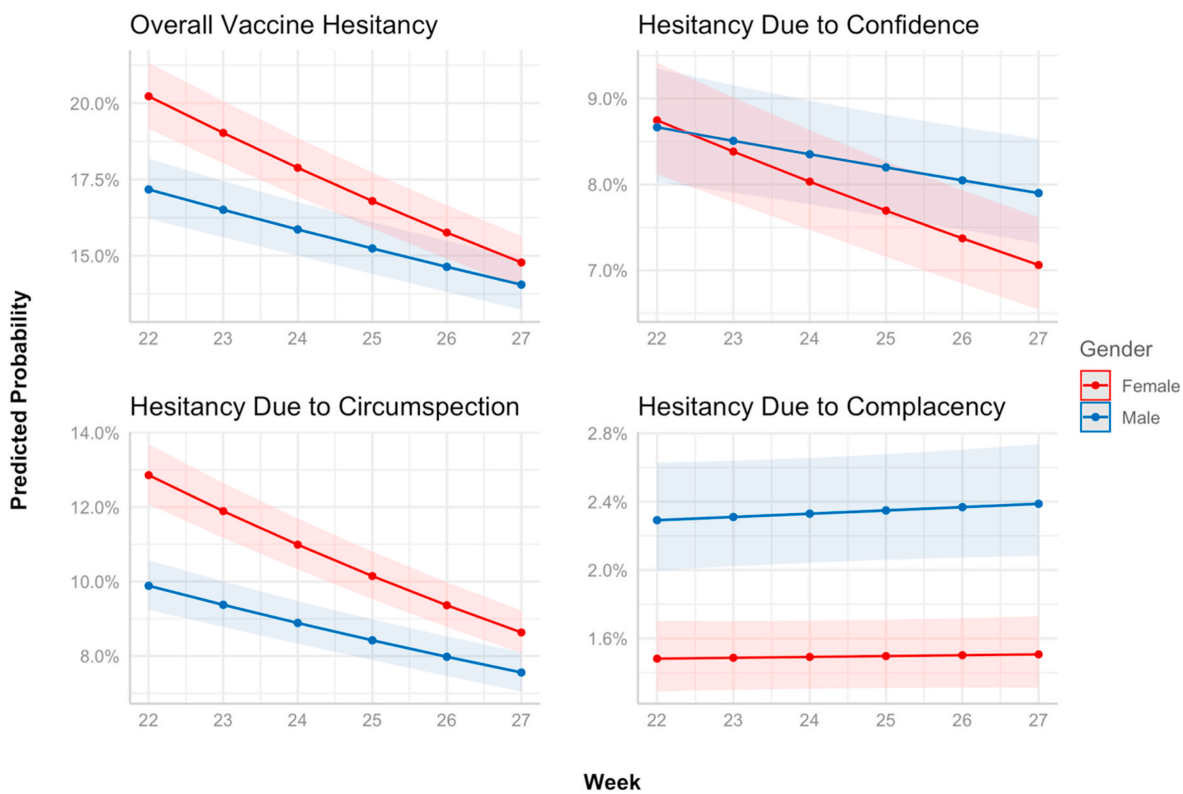

Fig. 8. Predicted Probability of Vaccine Hesitancy by Week and Gender. Note: Figure based on panel C in Table 3. Showing predicted probabilities and 95% confidence intervals.

A higher value thus indicates that the state leans more towards Republican.

We further include two state-level control variables. The first is subnational *Human Development Index (HDI)*, a composite index developed by the United Nations Development Programme to assess development level through jointly considering health, education, and economics. We use the 2018 HDI, the most recent data available, from the HDI Database of the Global Data Lab (2018). The second state-level control variable is the *proportion of non-Hispanic White population* of each state, which is pulled from the 2019 American Community Survey (ACS). For detailed information on state-level covariates, please see Appendix 4.

4. Methods

We first provide descriptive analyses to show the temporal, spatial, and sociodemographic variations of vaccine hesitancy. We then adopt multi-level mixed-effects logistic regression models with state-level random intercepts effects to predict each of the four vaccine hesitancy measures. To examine the temporal trend of vaccine hesitancy across sociodemographic groups, we include interaction terms between the data collection period (week) and three demographic variables: race, gender, and education. Similarly, to examine spatial variation of vaccine hesitancy across sociodemographic groups, we include interaction terms between state partisanship and the three demographic variables. To further explore the potential intersection in socioeconomic stratification of vaccine hesitancy, we include interaction terms between race and education, and between race and gender.

The HPS provides survey weights to produce estimates for the total persons age 18 and older living within households in the U.S. These weights were constructed to account for nonresponse, household size, and state demographics. In addition, the HPS created 80 replicate weights to calculate standard errors of estimates. For weekly descriptive estimates, we use survey weights and replicate weights following the HPS recommendation. For pooled descriptive estimates across six data collection periods, we divide replication weights by six to calculate standard errors. We do not use survey weights in the multilevel models because state-level design weights are not available and unweighted multilevel models tend to result in very similar inferential conclusions when compared to weighted estimates (Carle, 2009; Donnelly & Farina, 2021).

5. Findings

5.1. Descriptive variations and trends across demographic groups

We first present descriptive analyses on the temporal trends in each of the vaccine hesitancy measures across demographic groups and states.[7] First, Fig. 1 presents the overall trend of the four vaccine hesitancy measures. We observe a steady decline of overall vaccine hesitancy across the six data collection periods: the percentage of people with vaccine hesitancy dropped from 21.8% in week 22 to 15.9% in week 27. The decline is most visible among those with vaccine hesitancy due to circumspection, with the percentage decreasing from 16.2% to 11.0%. There is a smaller decrease in hesitancy due to confidence from 10.9% to 8.4%. Hesitancy due to complacency, however, remained steady across time at around 3.5%.

We next present trends of vaccine hesitancy across racial groups in Fig. 2. Overall, we observe the highest level of vaccine hesitancy among the Black and Other/Mixed groups, but the percentage of Blacks with overall hesitancy declined most dramatically from around 35% in week 22 to below 20% in week 27. Similar trends are observed for hesitancy due to confidence and circumspection, where the high percentages among Blacks declined visibly across time. In contrast, while the

[7] For the trend of each item used to construct the vaccine hesitancy measures, please see Appendix 8.

Table 4
Multilevel models predicting vaccine hesitancy with interaction between state partisanship and demographic variables.

	Overall	Confidence	Circumspection	Complacency
	(1)	(2)	(3)	(4)
Panel A: State Partisanship X Race (Reference = White)				
State Partisanship	1.31 *** (0.12)	1.23 *** (0.13)	1.25 *** (0.11)	1.19 *** (0.18)
State Partisanship X Asian	−0.28 (0.17)	−0.10 (0.27)	−0.29 (0.20)	0.27 (0.44)
State Partisanship X Black	−1.07 *** (0.08)	−1.10 *** (0.10)	−1.05 *** (0.08)	−1.02 *** (0.19)
State Partisanship X Hispanic	−0.44 *** (0.08)	−0.37 ** (0.11)	−0.66 *** (0.09)	0.11 (0.19)
State Partisanship X Other/Mixed	−0.15 (0.10)	−0.14 (0.13)	−0.21 (0.11)	−0.01 (0.20)
Panel B: State Partisanship X Education (Reference = Less Than High School)				
State Partisanship	1.16 *** (0.17)	1.20 *** (0.20)	0.74 *** (0.18)	1.19 *** (0.34)
State Partisanship X High School	−0.17 (0.13)	−0.25 (0.17)	0.13 (0.15)	−0.15 (0.32)
State Partisanship X Associate or Some College	−0.24 (0.13)	−0.38 * (0.16)	0.14 (0.15)	−0.36 (0.30)
State Partisanship X Bachelor	0.10 (0.13)	0.02 (0.17)	0.46 ** (0.15)	0.10 (0.31)
State Partisanship X Graduate	0.10 (0.14)	−0.04 (0.18)	0.52 *** (0.16)	0.19 (0.32)
Panel C: State Partisanship X Gender				
State Partisanship	0.97 *** (0.12)	0.86 *** (0.13)	0.92 *** (0.11)	0.99 *** (0.19)
State Partisanship X Male	0.31 *** (0.05)	0.35 *** (0.06)	0.26 *** (0.05)	0.20 * (0.10)

Note: *p < 0.05 **p < 0.01 ***p < 0.001. N = 443,680. Standard errors in parentheses. Multilevel logistic regression models with state-level random intercepts effects. Showing log-odds estimation. Each panel is a separate set of models with an interaction term between state partisanship and one sociodemographic variable (race, education, or gender) added to the base models shown in Table 2. All control variables at the individual and state levels are included in the models but omitted from the table. The main effects of the sociodemographic variables in the interaction terms are also included in the models but omitted from the table. The main effects of state partisanship show its effect in the reference group, and the interaction effects show the differences in the effects of state partisanship between the reference group and each focus group.

percentage of Whites with overall vaccine hesitancy declined slightly from over 20%–16%, it is mainly driven by the small decline in hesitancy due to circumspection; hesitancy due to confidence among Whites, on the other hand, stayed stable at around 10%. A similar pattern is observed for Hispanics. Hesitancy among Asians remained the lowest and declined very slightly across time. Last, hesitancy due to complacency among all racial groups stayed stable, with slightly higher levels among the White and Other/Mixed groups, and the lowest level among Asians.

Fig. 3 shows trends of vaccine hesitancy by gender. Overall, women were more likely to show vaccine hesitancy than men in the initial data collection period, but the percentage of women with vaccine hesitancy declined faster than men across time, and in the most recent data collection period the overall gender difference had disappeared. It is also worth noticing that the hesitancy of women was mainly driven by circumspection, thus it declined quickly as the situation evolved over time. When it comes to hesitancy due to confidence, there had been a slight decline among women but only mild fluctuation among men. In the most recent data collection period, a higher percentage of men were showing hesitancy due to confidence than women. Moreover, men were more likely to have hesitancy due to complacency, and the gender gap had been stable across the six data collection periods.

Fig. 4 further shows the trend across education groups. Overall, people with higher education levels were less likely to have vaccine hesitancy: by week 27, over 20% of people with a high school diploma or below indicates vaccine hesitancy, while the number is only about 10% for those with a bachelor's degree and 6% for those with a graduate degree. We observe a similar steady decrease in overall hesitancy across all four groups with at least a high school diploma or above; the trend is likely driven by hesitancy due to circumspection. Hesitancy due to confidence across these four groups remain stable at the first four data collection periods and only started to decline for those with a high school diploma, associate degree, or some college experiences from week 25 to week 27. It is also worth noticing that the group without a high school diploma or equivalent showed a different trend: the overall hesitancy declined between the first two data collection periods but fluctuated around 23% ever since; similar trends are observed for hesitancy due to confidence and circumspection. For hesitancy due to complacency, we again observe no obvious changes across all education groups.

5.2. Descriptive variations and trends across state partisanship

To examine variation in vaccine hesitancy across states, we first present the trends by state partisanship in the 2020 presidential election in Fig. 5. There is a higher level of vaccine hesitancy, overall and in all three dimensions, among those living in Republican states than Democratic states; the gap changed little despite a steady decline in overall hesitancy and hesitancy due to circumspection in both groups.

Fig. 6 further shows the scatterplots between state partisanship and state weighted means of vaccine hesitancy measures. There is a strong correlation between state partisanship and vaccine hesitancy: states that are more Republican (those with more votes for Trump relative to votes for Biden) tend to have a higher mean level of vaccine hesitancy overall and in all three dimensions. The Pearson's correlation coefficients are 0.84 for overall hesitancy, 0.82 for hesitancy due to confidence, 0.83 for hesitancy due to circumspection, and 0.74 for hesitancy due to complacency, all statistically significant. For detailed estimates on state-level vaccine hesitancy, please see Appendices 5 and 6. For a choropleth map showing the variation of overall hesitancy across states, please see Appendix 7.

5.3. Baseline multilevel models predicting vaccine hesitancy

We next use multilevel mixed-effects logistic regression models to predict vaccine hesitancy with individual and state-level covariates. Results from a set of base models are presented in Table 2. Each column is a model predicting a different vaccine hesitancy measure with the full sample.[8] Estimates are presented as log odds.

Results in Table 2 show significant variations across time, state partisanship, sociodemographic groups, and dimensions of vaccine hesitancy. First, men are overall less likely than women to have vaccine hesitancy; this gender difference is mainly driven by hesitancy due to circumspection. In fact, men are more likely to have vaccine hesitancy due to confidence and complacency than women. These results are consistent with descriptive results shown in Fig. 3.

[8] Anonymous Reviewer 2 suggested that we conduct similar analyses by restricting the sample to only those who exhibited vaccine hesitancy in the first place. We present the results of these alternative analyses in Appendix 15. The interpretation of these two sets of models will be different: our main analyses predict different dimensions of vaccine hesitancy out of all adults, while the alternative analyses predict different dimensions of vaccine hesitancy out of those with overall vaccine hesitancy. While many estimates are in the same directions, there are some noticeable differences. For example, in the alternative analyses, there is no significant difference between non-White groups and Whites in hesitancy due to circumspection if they have hesitancy in the first place. Please see Appendix 15 for detailed results.

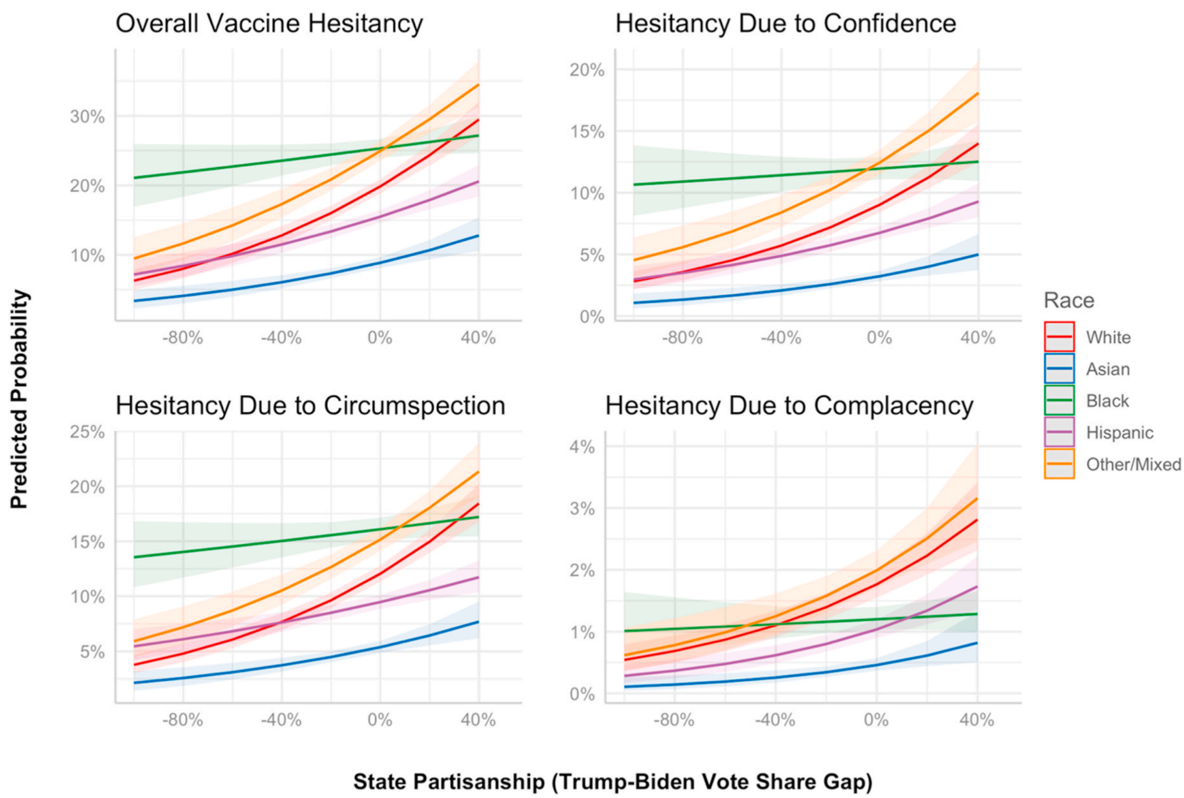

Fig. 9. Predicted Probability of Vaccine Hesitancy by State Partisanship and Race. Note: Figure based on panel A in Table 4. Showing predicted probabilities and 95% confidence intervals.

Second, Asians and Hispanics are less likely to have vaccine hesitancy than Whites across all hesitancy measures, with Asians having the lowest levels of hesitancy. The Other/Mixed racial group is more likely to have vaccine hesitancy than Whites across all measures. On the other hand, Blacks are more likely to have overall hesitancy and hesitancy due to confidence and circumspection than Whites; conversely, Blacks are less likely to have hesitancy due to complacency than Whites. These results are consistent with descriptive results shown in Fig. 2.

Third, while overall, people with higher education tend to be less likely to have vaccine hesitancy, we do observe that those with a high school diploma or equivalent are more likely to have hesitancy compared to those without a high school diploma. These results are consistent with the descriptive results shown in Fig. 4.

Fourth, when it comes to state partisanship, people in states leaning more Republican are more likely to have vaccine hesitancy in all measures. This is consistent with the descriptive results shown in Fig. 5.

In addition, at the individual level, vaccine hesitancy decreases as age increases; one year increase in age is associated with about a 3% decrease in the odds of having overall hesitancy (log odds = −0.03; odds ratio = 0.97). Currently married people are less likely to have vaccine hesitancy than those unmarried, except for hesitancy due to complacency. Number of children in household is positively correlated with vaccine hesitancy: one more child in the household is associated with a 26% increase in the odds of having overall hesitancy (log odds = 0.23; odds ratio = 1.26). In contrast, one more adult in the household is correlated with only about a 3% increase in the odds of having overall hesitancy (log odds = 0.03; odds ratio = 1.03). People who had COVID are more likely to have overall hesitancy (log odds = 0.26) and hesitancy due to confidence (log odds = 0.04) and circumspection (log odds = 0.20).

5.4. Multilevel models predicting vaccine hesitancy across time

To examine temporal changes in vaccine hesitancy across different demographic groups, we include interaction terms between data collection periods (week) and sociodemographic variables (race, gender, and education) into the base models. Results are presented in Table 3. Panel A shows models with the interaction between week and race, Panel B shows models with interaction between week and education, and Panel C shows models with interaction between week and gender. The main effects of the sociodemographic variables in the interaction terms are also included in the models but not presented in the table. The main effects of week reflect the difference between log odds of vaccine hesitancy between two adjacent data collection periods in the reference group. The interaction effects show the differences in the temporal trends between the reference group and the group at focus.

Results from column 1 in Panel A show that among Whites, the odds of having overall hesitancy decrease by approximately 5% in each data collection period (log odds = −0.05; odds ratio = 0.95). The overall hesitancy among Blacks declines by approximately 17% in each data collection period (log odds = −0.05−0.14 = −0.19; odds ratio = 0.83), significantly faster than Whites. The overall hesitancy among Hispanics declines by approximately 9% in each data collection period (log odds = −0.05−0.04 = −0.09; odds ratio = 0.91), slightly faster than Whites. The rates of temporal changes among Asians and the Other/Mixed group do not differ significantly from Whites. The patterns are similar for hesitancy due to confidence and circumspection as presented in columns 2 and 4. When it comes to hesitancy due to complacency, we only observe a significant difference in the rates of decrease between Blacks and Whites but not between Hispanics and Whites.

Based on models in Panel A of Table 3, we further plot the predicted probability of vaccine hesitancy measures across weeks by racial groups in Fig. 7. The four subplots clearly show the dramatically faster decrease among Blacks in all measures of vaccine hesitancy.

Table 5
Multilevel models predicting vaccine hesitancy with interaction terms between race and other demographic variables.

	Overall	Confidence	Circumspection	Complacency
	(1)	(2)	(3)	(4)
Panel A: Education X Race (Reference = White)				
Education	−0.54 *** (0.01)	−0.52 *** (0.01)	−0.47 *** (0.01)	−0.33 *** (0.01)
Education X Asian	0.17 *** (0.03)	0.14 ** (0.04)	0.14 *** (0.03)	0.12 (0.07)
Education X Black	0.25 *** (0.01)	0.28 *** (0.02)	0.28 *** (0.02)	0.16 *** (0.04)
Education X Hispanic	0.41 *** (0.01)	0.44 *** (0.02)	0.36 *** (0.02)	0.44 *** (0.03)
Education X Other/Mixed	0.21 *** (0.02)	0.26 *** (0.03)	0.20 *** (0.02)	0.23 *** (0.04)
Panel B: Male X Race (Reference = White)				
Male	−0.08 *** (0.01)	0.12 *** (0.02)	−0.17 *** (0.01)	0.46 *** (0.02)
Male X Asian	−0.14 * (0.07)	−0.22 * (0.10)	−0.13 (0.07)	−0.08 (0.17)
Male X Black	−0.50 *** (0.04)	−0.56 *** (0.05)	−0.48 *** (0.04)	−0.46 *** (0.09)
Male X Hispanic	−0.10 ** (0.03)	−0.14 *** (0.04)	−0.12 ** (0.04)	0.15 * (0.07)
Male X Other/Mixed	0.10 * (0.04)	0.08 (0.05)	0.08 (0.05)	0.22 ** (0.08)

Note: *p < 0.05 **p < 0.01 ***p < 0.001. N = 443,680. Standard errors in parentheses. Multilevel logistic regression models with state-level random intercepts effects. Showing log odds estimation. Each panel is a separate set of models with an interaction term between the race and another demographic variable (education or gender) added to the base models shown in Table 2. To facilitate interpretation, in models in Panel A, education is treated as a continuous variable ranging from 1 (less than high school) to 5 (graduate degree). All control variables at the individual and state levels are included in the models but omitted from the table. The main effects of race are included in the models but omitted from the table.

Panel B in Table 3 shows the rates of changes in vaccine hesitancy across groups with different education levels. The only difference we observe is that vaccine hesitancy among those with a graduate degree declines slightly faster compared to those without a high school diploma or equivalent. When it comes to different dimensions of hesitancy, this difference is only observed for hesitancy due to circumspection.

Panel C in Table 3 shows the rates of changes in vaccine hesitancy between men and women. The overall vaccine hesitancy declines slower among men than women: while for women, the odds of having vaccine hesitancy declines by about 8% each period (log odds = −0.08; odds ratio = 0.92), for men, the odds decline by about 5% each period (log odds = −0.08 + 0.03 = −0.05; odds ratio = 0.95). Similar patterns are observed for vaccine hesitancy due to confidence and circumspection. Hesitancy due to complacency, on the other hand, does not change significantly over time for men or women. These findings are clearly presented in Fig. 8, which plots the predicted probability of vaccine hesitancy across time for men and women based on models in Panel C of Table 3. It is worth noting that although women started with higher levels of overall hesitancy, it is mainly driven by hesitancy due to circumspection and declined quickly across time. Conversely, while men and women had similar levels of hesitancy due to confidence at the beginning, it declined faster among women and led to a visible gender gap in week 27. Moreover, men are more likely to have hesitancy due to complacency than women across the entire survey period.

5.5. Multilevel models predicting vaccine hesitancy across state partisanship

To examine variation in vaccine hesitancy across demographic groups in different states, we include interaction terms between state partisanship and demographic variables into the base models. Results are presented in Table 4. Panel A shows models with the interaction between state partisanship and race, Panel B shows models with interaction between state partisanship and education, and Panel C shows models with interaction between state partisanship and gender. The main effects of the sociodemographic variables in the interaction terms are also included in all models but not presented in the table.

Results in Panel A show that among Whites, vaccine hesitancy increases when they live in a more Republican state. This effect of state partisanship is significantly weaker among Blacks and Hispanics, while there is no significant difference between Asians and Whites. These findings are more evident in Fig. 9: all measures of vaccine hesitancy only slightly increase among Blacks when they live in a more Republican state, while for the Whites, state partisanship has a much stronger effect on the probability of vaccine hesitancy. Consequently, we observe different patterns of sociodemographic stratification in Republican-leaning and Democrat-leaning states: while in highly Democratic states, Blacks tend to have higher levels of vaccine hesitancy than the other racial groups, in highly Republican states, Whites and the Other/Mixed group tend to have higher hesitancy. This pattern is observed for all four measures and is especially evident for hesitancy due to complacency.

Panel B in Table 4 shows that among those without a high school diploma, state partisanship is significantly positively associated with vaccine hesitancy. This effect is relatively weaker for hesitancy due to circumspection (log odds = 0.74). Interestingly, for hesitancy due to circumspection, the effect of state partisanship is even stronger among those with a bachelor's (log odds = 0.74 + 0.46 = 1.20) or graduate degree (log odds = 0.74 + 0.52 = 1.26). Last, Panel C in Table 4 shows a significant gender difference in the effects of state partisanship: vaccine hesitancy increases faster than men for women as their state becomes more Republican.

5.6. Multilevel models with interaction between demographic variables

To examine the potential intersectionality between gender, race, and education, we include interaction terms between sociodemographic variables into the base models. Results are presented in Table 5. Panel A shows models with interaction between education and race, and Panel B shows models with interaction between gender and race. To facilitate the presentation and interpretation of results, we treat education as a continuous variable in these models. The main effects of race are included in all models but not presented in the table.

Results in Panel A show that among Whites, education is significantly negatively associated with vaccine hesitancy in all measures. One level increase in education is associated with a 42% decrease in the odds of having vaccine hesitancy (log odds = −0.54; odds ratio = 0.58). The effect of education, however, is significantly lower among other groups. Among Blacks, one level increase in education is associated with a 25% decrease in the odds of having overall hesitancy (log odds = −0.54 + 0.25 = −0.29; odds ratio = 0.75). Among Hispanics, one level increase in education is associated with only a 12% decrease in the odds of having overall hesitancy (log odds = −0.54 + 0.41 = −0.13; odds ratio = 0.88).

We further present these results in Fig. 10, which plots the predicted probabilities of having vaccine hesitancy across education levels by racial groups. We observe different patterns of racial stratification in vaccine hesitancy across education levels. Among those without a high school diploma, Whites tend to have the highest level of overall hesitancy, followed by Blacks and the Other/Mixed group. However, while hesitancy decreases as education increases, it decreases faster among Whites than Blacks and the Other/Mixed group; as a result, among those with some college experiences or above, the Black and Other/Mixed groups tend to have higher levels of hesitancy than Whites. This pattern is observed not only for overall hesitancy but also for hesitancy due to confidence and circumspection. Conversely, Whites tend to have higher levels of hesitancy due to complacency than Blacks even among those with higher levels of education. It is also worth noting that even among

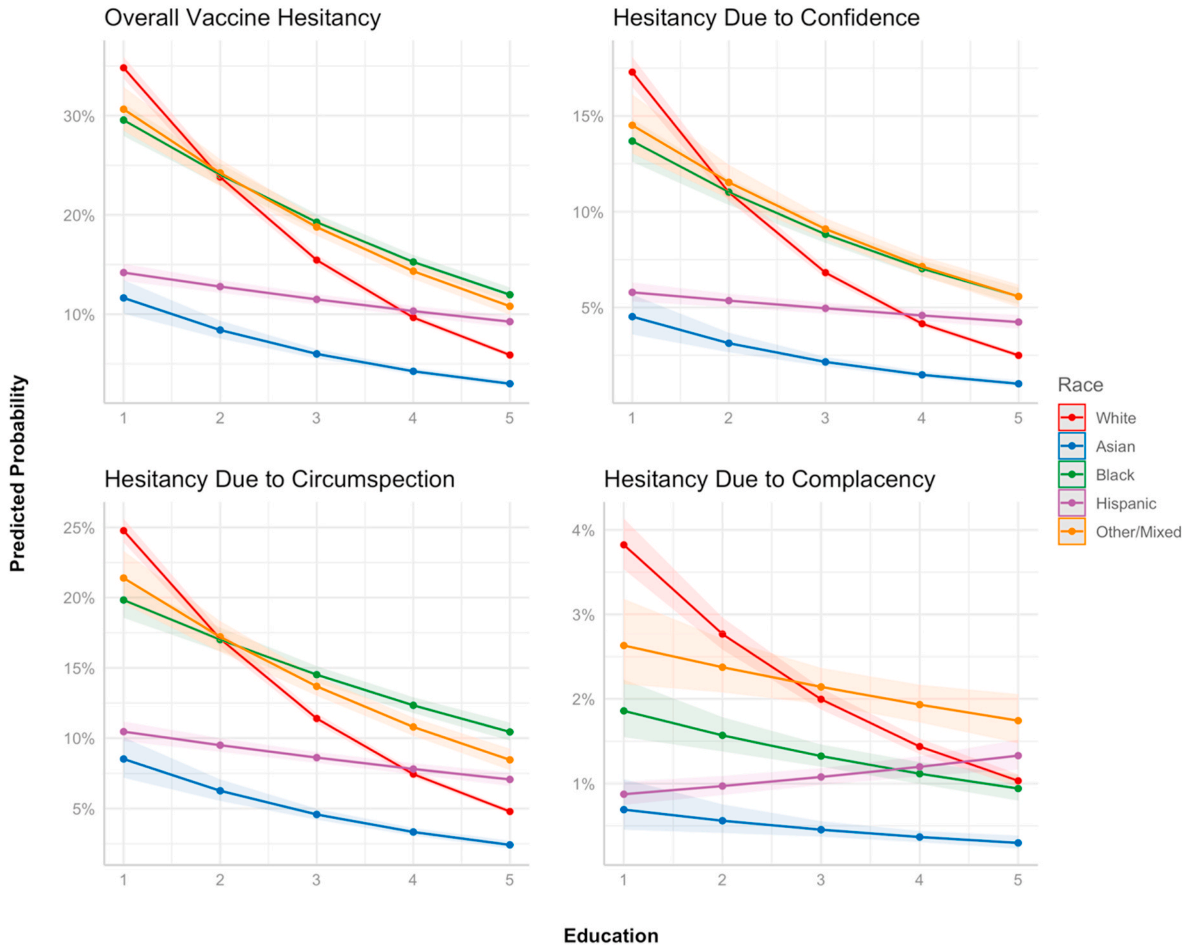

Fig. 10. . Predicted Probability of Vaccine Hesitancy by Race and Education. Note: Figure based on panel A in Table 5. Showing predicted probabilities and 95% confidence intervals. Education is treated as a continuous variable (1 = Less than high school; 2 = High school or equivalent; 3 = Associate degree or some college; 4 = Bachelor's degree; 5 = Graduate degree).

those with low education levels, Hispanics and Asians tend to have relatively low levels of hesitancy, and hesitancy can further decrease among Asians as education increases.[9]

When it comes to the intersection between race and gender, Panel B in Table 5 shows significantly different gender stratification patterns across racial groups, as shown in Fig. 11. The gender difference is largest among Blacks: the probability of Black women to have overall hesitancy is almost 10 percentage points higher than that of Black men. This is also true for hesitancy due to confidence and circumspection. On the other hand, men are more likely to have hesitancy due to complacency than women across all racial groups except for Blacks.[10]

6. Discussion

This study utilizes the most updated U.S. HPS data from January to March 2021 to examine factors associated with disparities in vaccine hesitancy. Results reveal important variations of vaccine hesitancy across time, space, and sociodemographic groups, addressing new challenges and possibilities to improve vaccination rates for COVID-19 and to reduce vaccine hesitancy more broadly.

First, the partisan divide embedded in the COVID-19 vaccine hesitancy is concerning but only tells one side of the story. State partisanship had a strong correlation with state percentage of people with vaccine hesitancy, which echoes the long-standing finding that the disparity in vaccination rates and vaccine attitudes in the U.S. reflects a clear partisan divide (e.g., Bernstein et al., 2016; Mesch & Schwirian, 2015). Moreover, the partisan gap did not narrow over time as some other disparities did, raising concerns over the vaccination outcomes in more Republican states. On the other hand, the variations across the three dimensions of vaccine hesitancy and the sociodemographic stratification patterns indicate that hesitancy towards COVID-19 vaccines is not simply a partisan issue shaped by misinformation and conspiracy theories. Instead, it involves complex concerns related to confidence and circumspection issues that may have their roots in structural inequality but could change across time as the situation evolves.

Second, consistent with previous studies showing persistent racial disparities in vaccination uptake and attitudes (e.g., Logan, 2009; Quinn et al., 2017; Wang et al., 2014) and recent evidence of racial disparities in COVID-19 vaccine intentions (e.g., Callaghan et al., 2021; Latkin et al., 2021), we find significant racial differences in hesitancy towards COVID-19 vaccines. Extending previous studies, we further point out important differences in the determinants of vaccine hesitancy and temporal and spatial changes across racial groups. Blacks are significantly more likely to develop vaccine hesitancy than other racial/ethnic groups during early periods of vaccine release – in the first data collection period (January 6–18, 2021), nearly 35% of Blacks show vaccine hesitancy, more than 10 percentage points higher than Whites and Hispanics, and over 20 percentage points higher than Asians. This

[9] For a descriptive visualization on the intersection of education and race in week 27, please see Appendix 9.

[10] For a descriptive visualization on the intersection of gender and race in week 27, please see Appendix 10.

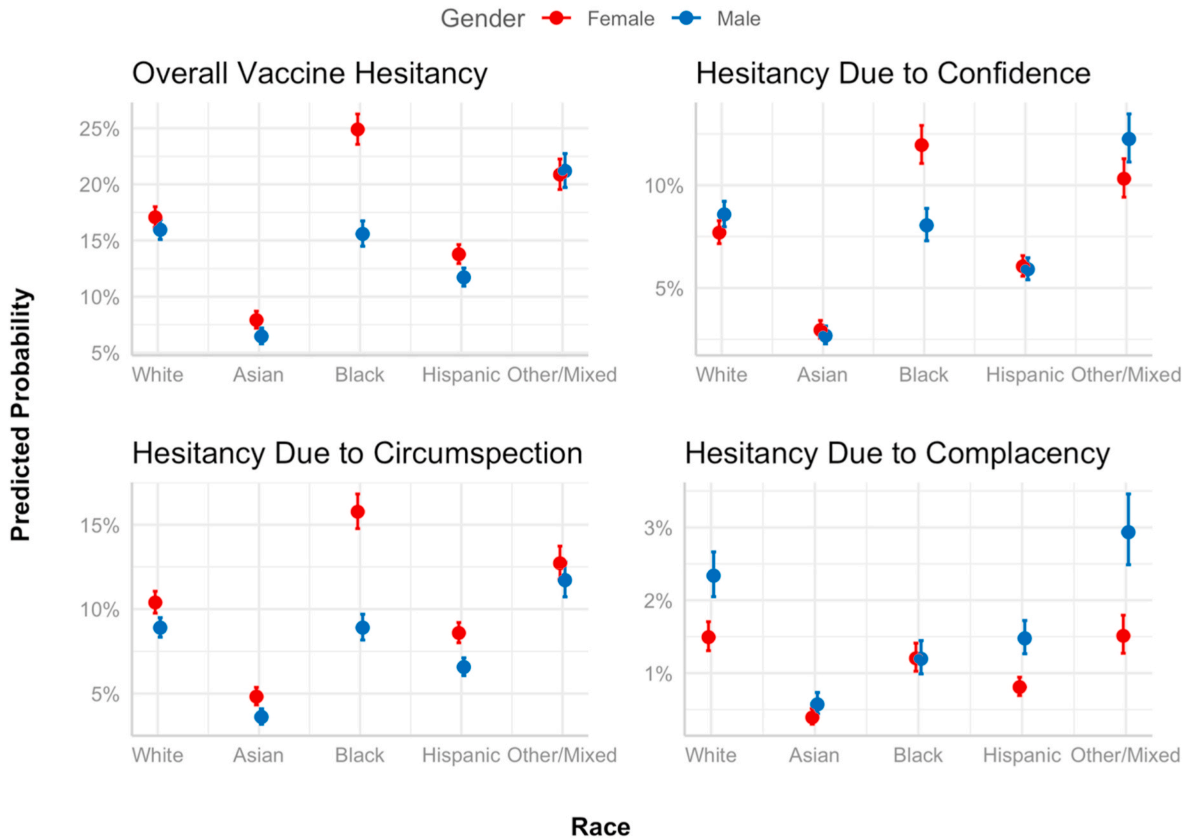

Fig. 11. Predicted probability of vaccine hesitancy by race and gender.

hesitancy among Blacks, however, is largely driven by confidence and circumspection issues but not so much by complacency issues. This means Blacks are hesitant not because they underestimate the risks of COVID-19, but because they have concerns with the effectiveness and side effects of COVID-19 vaccines and incline to calculate the costs and benefits carefully before making a vaccination decision.

Moreover, vaccine hesitancy among Blacks declines dramatically across time, faster than any other racial groups. In fact, in the most recent data collection period (March 17–29, 2021), the predicted probability of vaccine hesitancy among Blacks has decreased to the same level as that of Whites – including overall hesitancy and hesitancy due to confidence and circumspection. This is consistent with the recent trend in the actual vaccination rate, which has shown a narrowing of racial gaps (Ndugga et al., 2021). As of June 28, 2021, the share of recent COVID-19 vaccinations received by Blacks for the first time surpassed their share of the total population (Bunis, 2021). While the causal mechanisms of these changes are beyond the scope of this study, these results are encouraging and point to promising ways to reduce racial disparities in vaccination inequality more broadly. Some barriers to vaccination that disproportionately affect Black communities, such as low confidence in the system and limited access to the internet and transportation, could be addressed with community-based initiatives. For example, Loma Linda University, which serves as the largest vaccination site in San Bernardino, California, developed a three-tiered approach to effectively reach the Black community. This approach involves "the engagement of Black faith leaders, the delivery of education about COVID-19 vaccinations by a Black health-care professional, and the development of a multidisciplinary mobile vaccination effort, by holding the vaccination clinic in a church parking area in a mostly Black community" (Abdul-Mutakabbir et al., 2021). Considering the unprecedented efforts on public communication and administrative support for the COVID-19 vaccination process, the gradual decline in vaccine hesitancy that we observed over time sends an optimistic signal. It is likely that similar initiatives during the COVID-19 vaccination processes - such as engaging local community leaders and professionals, increasing the transparency of the vaccine development and approval processes, offering accessible information regarding the effectiveness and side effects of vaccines, providing free vaccination regardless of insurance status, expanding vaccination sites and developing more accessible scheduling systems, and making other community-specific engagement endeavors - could effectively reduce racial disparities in vaccine uptake and attitudes more broadly.

Furthermore, while Hispanics tend to have a relatively lower level of hesitancy than Blacks (a similar level as Whites), it is worth noticing that education seems to have a much weaker impact on vaccine hesitancy among Hispanics compared to other racial groups. The difference in predicted probabilities of having vaccine hesitancy between those without a high school diploma and those with a graduate degree is only 5 percentage points for Hispanics, while it is almost 30 percentage points for Whites and over 15 percentage points for Blacks. Even for Asians with an already very low level of vaccine hesitancy among those without a high school diploma, education still matters more than it does for Hispanics. The unique phenomenon of persistent vaccine hesitancy across all education levels among Hispanics is worth more in-depth investigation. It may require very different strategies to effectively reduce vaccine hesitancy within the Hispanic community.

Third, our findings point to important gender differences as well. Consistent with previous evidence on gender differences in vaccination behaviors and attitudes (e.g., Callaghan et al., 2021; Flanagan et al., 2017; Latkin et al., 2021; Pulcini et al., 2013), we observe a higher level of overall vaccine hesitancy among women than men in early periods. However, when examining different dimensions of vaccine hesitancy, our findings point out that women are more likely to develop hesitancy due to circumspection, and this kind of hesitancy declines faster than hesitancy due to confidence and complacency. In fact, in the last data collection period, the gender gap has disappeared in overall hesitancy.

Moreover, while a persistent five percent of men have hesitancy due to complacency - which means they believe COVID-19 is not that risky to them - across the six survey periods, rarely any women develop hesitancy for the same reason (see Fig. 3). The association between state partisanship and vaccine hesitancy is also weaker among women than men. These results may indicate that women are more likely to adjust their vaccine attitudes according to evolving information and rely less on ideological factors than men do. Efforts to improve vaccine uptake for adults and children may thus be more effective targeting women and more challenging targeting men.

Fourth, our findings also reveal an important intersection between race and gender. We observe the highest level of hesitancy among Black women. In fact, after adjusting for individual- and state-level covariates, the predicted probability of having vaccine hesitancy for Black men is even slightly lower than that of White men and women, while the predicted probability for Black women is almost 10 percentage points higher. The same pattern is observed for hesitancy due to confidence and circumspection, while very few Black women have hesitancy due to complacency. These findings are consistent with previous literature linking vaccine hesitancy to historical and current systemic racism and discrimination (e.g., Quinn et al., 2017, 2016; Savoia et al., 2021). While the most marginalized group develops the lowest level of trust in the government and health systems, the resulting high vaccine hesitancy and low vaccine uptake could further reproduce inequality in immunization and health outcomes. It is thus extremely important to recognize intersectionality in vaccination and adequately address the concerns of the most disadvantaged groups. This is not only about successfully combating the pandemic, but also about equity and justice in health.

Last, the interaction effects of state partisanship with individual-level variates, particularly race, should alarm researchers and policymakers with an inconvenient truth. Whereas we witnessed a promising drop of vaccine hesitancy over time among the Black community, it is worth noting that unlike other racial/ethnic groups, Blacks living in Democratic states did not demonstrate a much lower level of vaccine hesitancy than their counterparts who live in Republican states. This indicates that vaccine hesitancy among Blacks, particularly hesitancy caused by confidence and circumspection issues, is nearly universal across the nation and not determined by local partisanship context. As a result, we observe a larger racial disparity in vaccine hesitancy in states that are more Democratic, where other racial groups tend to have low levels of vaccine hesitancy. These findings call for more targeted policies and strategies to improve vaccination rates according to local and community contexts.

7. Conclusion

This study is not without limitations. First, analyses in this study remain correlational rather than causal. Although we include individual- and state-level covariates to control for observed heterogeneity, unobserved confounders could bias the findings. Second, HPS uses respondents' own vaccination behaviors to screen for vaccine hesitancy-related questions; it does not ask about parents' attitudes on vaccinating their children. However, parents could have different concerns and perceived risks for themselves and their children; considering the varying risk levels of COVID-19 based on age, it is very likely that some parents have no hesitancy to vaccinate themselves but become hesitant when vaccinating their children. As the COVID-19 vaccine use authorization is expanding to the younger population (Neergaard & Choi, 2021), it has become increasingly important to understand parents' plans and attitudes by collecting more targeted information. Third, the HPS answer options regarding reasons for vaccine hesitancy miss some important factors found in previous literature, such as past experiences with vaccination (Busse et al., 2011) and philosophical, moral, or religious convictions (Ruijs et al., 2012; Streefland, 2001). Moreover, HPS does not gather more detailed information on respondent ethnicity. As a result, we are unable to examine the heterogeneity within racial groups, which may mask substantial differences across ethnic subgroups, especially within the Asian and Hispanic communities.

Despite the limitations, findings of this study underscore concerning inequality and intersectionality underlying the COVID-19 vaccination process. The COVID-19 crisis poses an unprecedented challenge to the world. The disease's highly contagious nature and the lack of effective medication treatment so far make vaccines our most hopeful weapon to combat the pandemic. Reducing vaccine hesitancy, particularly among the disadvantaged sociodemographic groups, is thus imperative for scholars and policymakers to address structural inequalities in the impacts of COVID-19. While recent data suggesting a narrowing racial gap in COVID-19 vaccine uptake, White people still have a higher vaccination rate than Hispanic and Black people in most of the reporting states (Ndugga et al., 2021). CDC has been making efforts to bring vaccines to vulnerable communities to "ensure that no persons are left behind" (Painter et al., 2021); however, it is crucial to recognize that accessibility alone may not adequately address concerns within these communities. Well-targeted strategies in accordance with community-specific needs are at the core to improve COVID-19 vaccination and reduce sociodemographic disparities. Scholars and local practitioners have proposed a series of strategies to reduce vaccine hesitancy in minority populations and to achieve vaccination equity, including using multiple languages in various forms of communications to dispel misinformation and promote vaccination, developing outreach programs featuring community leaders and local health care providers whom the community members find more trustworthy and relatable, creating more flexible and accessible appointment systems to remove technological barriers, organizing virtual town hall meetings and dialogues alike to directly address people's vaccine-related questions and doubts, and so on (Abdul-Mutakabbir et al., 2021; Hildreth & Alcendor, 2021). These strategies not only help to improve vaccination equity for now but could remain important in the longer term as variants of SARS-CoV-2 are spreading rapidly and vaccine boosters may later become necessary to maintain immunity (Yen, 2021).

Findings of this study also shed light on our understanding of vaccine hesitancy and enlighten future strategies to reduce sociodemographic disparities in vaccination. The unprecedented efforts to promote vaccination during the COVID-19 pandemic have shown promising outcomes in reducing vaccine hesitancy and the associated disparities. Policymakers, health care providers, and civil society should join hands to take proactive, targeted, and community-based efforts to reduce vaccine hesitancy for other vaccine-preventable diseases and improve broader health equity.

CRediT authorship contribution statement

Ran Liu: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. **Gabriel Miao Li:** Conceptualization, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

None.

Acknowledgement

The authors gratefully acknowledge support to Ran Liu from the University of Wisconsin–Madison, Office of the Vice Chancellor for Research and Graduate Education with funding from the Wisconsin Alumni Research Foundation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssmph.2021.100896.

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