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Cognitive ability, health policy, and the dynamics of COVID-19 vaccination

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Title: Cognitive ability, health policy, and the dynamics of COVID-19 vaccination

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Abstract: We examine the relationship between cognitive ability and prompt COVID-19 vaccination using individual-level data on more than 700,000 individuals in Sweden. We find a strong positive association between cognitive ability and swift vaccination, which remains even after controlling for confounding variables with a twin-design. The results suggest that the complexity of the vaccination decision may make it difficult for individuals with lower cognitive abilities to understand the benefits of vaccination. Consistent with this, we show that simplifying the vaccination decision through pre-booked vaccination appointments alleviates almost all of the inequality in vaccination behavior.

Keywords
Intelligence; Vaccination; Covid-19; Nudge; Administrative data; Twin-design

I. Introduction

The primary policy tool to end the COVID-19 pandemic in most Western countries was to achieve a high vaccination rate as quickly as possible (Randolph and Barreiro 2020; Sridhar and Gurdasani 2021). While many individuals took the first opportunity to get vaccinated, others were slower, and a non-negligible share refrained vaccination, thus putting both themselves and others at an unnecessary risk of severe COVID-19 infection. This suggests that a one-size-fits-all approach, such as the information-based opt-in vaccination strategy adopted in many countries, was effective in that it resulted in a high and prompt vaccination rate in a large share of the population. However, it also suggests that it was ineffective for a smaller, but still substantial part of the population. Alternative approaches to overcome vaccine hesitancy have been tested but with varying results (e.g. Dai et al. 2021; Ho et al. 2021; Liu, Zhao, and Zheng 2022; Bonander, Ekman, and Jakobsson 2022; Patel et al. 2022; Milkman et al. 2022; Barber and West 2021, Acharya and Dhakal 2021; Campos-Mercade et al. 2021; Karaivanov et al. 2022; Schneider et al. 2023). However, the causes of this heterogeneity in vaccination behavior are poorly understood but crucial for designing effective vaccination programs.

While cognitive ability is correlated with a favorable social background, which in turn is related to better health (Deary et al. 2021), psychologists have argued that there may also be a direct link between cognitive ability and health-related behaviors. The argument is that many health decisions faced by individuals are cognitively demanding since they involve processing of complex information (Gottfredson 2004; Gottfredson and Deary 2004). Regarding COVID-19 vaccination, several pros and cons that are hard to assess must be weighed against each other, such as your own risk of getting the disease, risk of side effects, benefits to others, and the potential advantages of waiting for more information (Machingaidze and Wiysonge 2021). Cognitive ability has been shown to be positively related to a wide range of health behaviors in the domains of prevention, protection, and care (Deary et al. 2021). This link may explain why lower scores on cognition tests are consistently linked to higher morbidity and premature mortality (Deary et al. 2021; Calvin et al. 2011; Öhman 2016), including due to COVID-19 (Batty, Deary, and Gale 2021). Surveys conducted prior to the rollout of the COVID-19 vaccine (Murphy et al. 2021; Batty et al. 2021) or very early into the vaccination campaign (Acar-Burkay and Cristian 2022) indicate that individuals with higher cognitive abilities had a more positive attitude towards vaccination compared to individuals with lower cognitive abilities.

Intentions, however, constitute imperfect indicators for actual take-up (Harris, Maurer, and Lurie 2009; Wang et al. 2022) and are silent in terms of how quickly individuals would take the vaccine when it becomes available. Furthermore, the practical importance of a positive relationship between cognitive ability and vaccination largely depends on whether cognitive ability serves as a proxy for social background or whether it has a direct impact on vaccination behavior. Finally, it is important to figure out how to design policies raising the vaccination rates of individuals with lower cognitive abilities, as it could improve public health and reduce health inequality.

In this paper, we analyze how cognitive ability is related to *if* and *when* individuals get vaccinated against COVID-19 and whether simplifying the vaccination decision by providing pre-booked vaccination appointments (opt-out policy) may alleviate heterogeneity in vaccination behavior. For this purpose, we use individual-level administrative data from Sweden covering 750,381 men and 2,703 women aged 42–59, in 2021. We match information on their COVID-19 vaccinations with scores on a cognitive ability test, capturing general intelligence (Mårdberg and Carlstedt 1998), that was taken at about 18 years of age as part of the Swedish military enlistment procedure, which was mandatory for men and voluntary for women. The test scores are reported on a stanine scale (min=1, max=9, mean=5, standard deviation=2).

We find that cognitive ability is positively associated with swift COVID-19 vaccination. At each point in time, during a 360 days period following the vaccine rollout, there is a positive monotonic relationship between cognitive ability and the rate of first dose vaccinations. For example, a vaccination rate of 80% is reached after approximately 50 days in the group with the highest cognitive ability score and after 180 days in the group with the lowest score. Moreover, we show that the relationship is remarkably robust; it remains strong when using a twin design (3,375 twin-pairs) to control for confounders (e.g. social background) and it is not mediated away by socioeconomic characteristics (i.e. education, income, marital status, parenthood). Finally, we evaluate a regional policy regarding the use of pre-booked vaccination appointments and find that such a simple policy increases vaccination uptake disproportionately more among those with lower cognitive abilities, leaving them with a vaccination rate comparable to that of high cognitive ability individuals in the absence of the policy. Given that individuals with lower cognitive abilities are relatively more susceptible to many health risks, including COVID-19 infection, such a policy is likely to be associated with large welfare gains for this group. Our findings also imply that if everyone got vaccinated as quickly as individuals with a high cognitive ability, the pandemic would likely have ended earlier, with fewer lives lost and with lower costs for society.

II. Data and Research design

A. *Data*

The analyses are based on individual-level data from several administrative registers in Sweden.[1] The study population consists of all men and women who enlisted for military service in Sweden between 1979 and 1997. During this period, enlistment was mandatory for men the year they turned 18 or 19.[2] Women could not enlist for military service before 1980 but were then allowed to do so on a voluntary basis. The study population thus covers almost the entire population of Swedish men born between 1962 and 1979, in total 750,381, as well as the sample of women who enlisted during the period of 1980–1997, in total 2,703.

In addressing the role of confounders, we also analyze the sub-sample of 6,750 twin brothers (3,375 twin-pairs) in the enlistment records (identified by shared biological mother and year and month of birth).

See Appendix Table S1 for descriptive statistics for the study population, the sub-sample of twin brothers, and the sample of women.

In Sweden, all individuals have a personal identity number (PIN). Swedish administrative registers contain PINs, which enables us to link information from the following registers: The Swedish Military Archives, The Swedish Vaccination Register, held by the Swedish Public Health Agency (PHA), The Swedish Tax Agency’s Income and Tax Register, held by Statistics Sweden (SCB), The Multi-Generation Register, held by SCB, and The Education Register, held by SCB.

Cognitive ability.—We collect data on cognitive ability from the Swedish Military Archives, which keep records of the test scores from the Swedish Armed Forces’ enlistment procedure.

Cognitive ability is assessed through a test, similar to the Wechsler Adult Intelligence Scale (Ludvigsson et al. 2022), aimed at eliciting the individual’s logical, verbal, and spatial abilities as

[1] The Swedish ethical review authority (Etikprövningsmyndigheten) has approved the research conducted in this study (reference number 022-01136-02).

[2] After 1997, the Swedish Armed Forces had to cut costs and could not afford to let all men go through the enlistment procedure. Hence, the men who participated in the enlistment procedure after 1997 are no longer representative of all physically and mentally able men of their birth cohort.

well as technical comprehension. The tests scores are standardized to create a score on a stanine (standard 9) scale (integers 1 to 9, with 9 representing the highest test scores), which approximates a normal distribution with a mean of five and a standard deviation of two. This means that 3-4% of the population scores 1 and 9, respectively, and as we move towards the mean the share increases and 24% score a 5 (see Appendix Table S2, for more details on the distribution of the test scores). We refer to this measure as cognitive ability. Psychologists have shown that the test offers a valid and reliable measure of general intelligence (Mårdberg and Carlstedt 1998). It corresponds with intelligence quotient (IQ) in that 1 corresponds to IQ<76, 5 to 96<IQ<104, and 9 to IQ>126 (Öhman 2016). The test scores have also been shown to be highly correlated with scores on a similar cognitive ability test taken at the age of 50–65 (Rönnlund, Sundström, and Nilsson 2015), suggesting that it is a good predictor of intelligence throughout adulthood.

For the regression analyses, we standardize the cognitive ability scores to have a mean of zero and unit variance to account for the slight drift in scores over cohorts (Edin et al. 2022).

The enlistment tests were implicitly incentivized since there was essentially no exemption from doing the military service, conditional on enlistment, and better test scores led to more attractive placements. Consequently, the cognitive ability measure is likely to be a reliable measure of true intelligence.

The cognitive ability scores have also been used extensively in empirical research (e.g. Batty et al. 2009; Lindqvist and Vestman 2011; Öhman 2016; Edin et al. 2022).

COVID-19 Vaccinations.—Data on COVID-19 vaccinations are obtained from The National Vaccination Register, which contains the date of each vaccination of each Swedish resident since the roll-out of the vaccination program in December 2020. The data that we have access to contain information about all vaccinations until June 2022. Consequently, we can characterize the relationship between cognitive ability and vaccinations at every point during a period of one and a half years.

For the analyses, we create several variables using these data. A common feature of these variables is that they are based on the date when the vaccine became available to the individual. Availability of the vaccine was determined by the individual's age and region of residence. We use data on the full population of vaccinated individuals in Sweden born in 1960 or later (both men and women) to determine the date when the vaccine became available to them. More specifically, we define the first available date by calculating the share of vaccinated individuals per day by birth year and region of residence.[3] We define the first available date as the day when more than 1 percent of the group (birth year and region) had undergone the vaccination. Individuals having obtained the vaccine before that date are dropped from the analysis, since their decision to get vaccinated is less voluntary, either because they work in the health care or elderly care sectors or belong to prioritized risk groups, such as organ transplant recipients.

We create several outcomes to capture the timing of vaccinations. The first set consists of binary variables intended to capture whether or not the individual has taken the first dose within 90, 180, 270, or 360 days after the vaccine became available (given age and region of residence).

We also create a binary variable capturing whether the individual has taken the second dose within 180 days of availability of the first dose (given age and region of residence).

The last outcomes are binary variables which take the value one if at least one of the individual's children aged 12–15 has taken at least one dose within either 90 or 180 days after the vaccine became available to the child (given age and region of residence).

[3] Information about birth year and region of residence is available in the register.

Personality.—We collect data from the Swedish Military Archives regarding the scores on a personality test conducted during the enlistment process. The purpose of this test is to evaluate the enlistee's ability to fulfill the requirements of military service and armed combat and is based on a 20–30-minute long interview with a psychologist. The psychologist has information about the enlistee's scores on the cognitive ability test, school grades, and responses to 80 questions regarding family conditions, social relationships, etc. Although the exact evaluation procedure is confidential, it is commonly known that high emotional stability, persistence, sociality, willingness to assume responsibility, and ability to take initiative yield higher test scores (Grönqvist, Nilsson, and Robling 2020). The scores are reported on a stanine scale. This measure is commonly referred to as non-cognitive (Lindqvist and Vestman 2011), while we in this paper refer to it as personality and use it as a control variable.

In addition, we have collected data on several individual characteristics from the population registers at SCB. The variables, which are listed below, are treated as mediators in the econometric analysis and are measured in 2019 to ensure that they are unaffected by the pandemic.

Education.— Education is measured as the number of years of completed education as reported in the Education Register.

Income.— Income is measured as the logarithm of the sum of annual pre-tax labor and capital incomes as reported in the Income and Tax Register.

Married.—An indicator variable for being married (=1), as reported in the Income and Tax Register.

Parent.— An indicator variable for being a parent of at least one living child (=1) as reported in the Multi-Generation Register.

Municipality of residence.—Obtained from the civil registration address reported in the National Vaccination Register (PHA) at the time of the first dose. For individuals who do not appear in the National Vaccination Register, we obtain information on municipality of residence as of December 31, 2021, from the Income and Tax Register.

B. *Research design*

The purpose of the statistical analysis is to provide interpretable estimates of the relationship between cognitive ability and vaccinations and to account for observable and unobservable factors that may confound this relationship. We also want to assess whether the relationship is direct or mediated through other variables.

Although there are theoretical arguments and empirical evidence pointing towards a positive association between cognitive ability and vaccination, there are many reasons why such relationship may not be causal.

A key concern is that cognitive ability is correlated with other factors, which, in turn, are correlated with the decision to get vaccinated. For example, more intelligent individuals are likely to have more intelligent parents who, in turn, influence the health behaviors of their children, both genetically and through their own behaviors (Deary et al. 2021). This argument is not only valid at the family level, but partially also at the peer, school, and neighborhood levels.

More intelligent individuals are also more likely to have grown up in privileged families and neighborhoods (Chetty et al. 2014). As a result, they may have been less exposed to environmental risks (Banzhaf, Ma, and Timmins 2019) detrimental to cognitive development, such as lead (Grönqvist, Nilsson, and Robling 2020), air pollution (Simeonova et al. 2017), or in utero alcohol exposure (Nilsson 2017). All these environmental factors may affect the health of the child and thereby also have a direct impact on the individual's incentive to take the vaccine, meaning that the correlation between cognitive ability and vaccination behavior may be spurious.

Our strategy to control for confounding factors due to unobserved family environment background is to exploit variation in cognitive ability within twin-pairs. Within-twin-pair estimation has been used extensively for similar purposes in economics and other fields (Behrman 2016). Since twins experience a similar in utero environment, share parents and rearing, commonly go to the same school, and are influenced by the same peer groups when growing up, this approach effectively accounts for family and environmental confounders (Bouchard and McGue 2003). It also partially accounts for confounders due to genetics. Any remaining variation thus stems from variation in non-shared environments and non-shared genetics. In practice, we limit the analysis to a sample of the 3,375 pairs of twin brothers who have completed the enlistment procedure and estimate regression models with twin-pair fixed effects, see below.[4]

In Appendix Figure S1 we show that there is substantial variation in cognitive ability between twin brothers, as 69% of the twins differ by at least one stanine point, while 26% of the twins differ by at least one standard deviation. Furthermore, the twins are remarkably similar to the population of enlisted men in terms of socioeconomic characteristics and, importantly, also with respect to the relationship between cognitive ability and vaccination (see Appendix Figure S2 and tables S1–S2).

Yet, it is still possible that the association may be confounded by personality traits, other than cognitive ability, correlated with both cognitive ability and vaccination behavior. For example, the cognitive ability measure we use is positively correlated with the scores on the personality test conducted during the enlistment process, which, in turn, is correlated with vaccination behavior. As a result, we control for the personality measure in the regression models.

Moreover, we acknowledge that an effect of higher cognitive ability on vaccination may be explained by various mediating or moderating mechanisms. For instance, individuals with higher cognitive ability are more likely to have acquired more education and earn more (Lindqvist and Vestman 2011), be married (Aspara, Wittkowski, and Luo 2018), and have fewer children (Meisenberg 2010). Each of these factors may also be related to vaccination behavior.

Finally, to account for the possibility that individuals with a higher cognitive ability live in areas with better health care services, thus making it easier for them to get vaccinated, we estimate models with municipality of residence fixed effects.[5] The resulting, full regression model looks as follows:

$$y_{i,j} = \alpha + \beta C_{i,j} + \gamma P_{i,j} + \rho \boldsymbol{X}_{i,j} + \delta_j + \varepsilon_{i,j} \qquad (1)$$

where $y_{i,j}$ is the outcome (vaccination of first dose within 90, 180, 270, or 360 days after the vaccine became available) of individual i in twin-pair j. $C_{i,j}$ refers to cognitive ability test score, standardized by enlistment cohort to have a mean of zero and unit variance. $P_{i,j}$ refers to

[4] The sample contains both monozygotic and dizygotic twins. In the overall population of twins, the incidence of monozygotic (dizygotic) twins is about 30 percent. In a population of same sex twins, the incidence is expected to be 50 percent.
[5] Municipalities are smaller administrative areas than the health care regions, and there is a total of 290 municipalities in Sweden.

personality test score, standardized by enlistment cohort to have a mean of zero and unit variance. $\boldsymbol{X}_{i,j}$ is a vector of mediators, δ_j is a twin-pair fixed effect, and $\varepsilon_{i,j}$ is an error term.

The structure of the statistical analysis is that we begin by estimating the raw relationship between cognitive ability and the vaccination outcomes, that is model 1 without any of the controls or mediators. This is done for both the full population of enlisted men and the sample of twin brothers. We then focus on the twin sample and asses how the relationship between cognitive ability and vaccination changes when we add controls and mediators, both one at the time and all simultaneously.

The models are estimated using an ordinary least square estimator (OLS) with heteroscedasticity-robust standard errors, except in models with twin fixed effects where they are clustered at family level to correct for interdependence within the twin-pair.

III. Results

A. *Cognitive ability is strongly and positively related to swift take-up of COVID-19 vaccine*

We begin by investigating the relationship between cognitive ability and COVID-19 vaccination in the full sample of enlisted men. Panel A in Figure 1 displays the daily cumulative rate of first dose vaccinations by cognitive ability test scores, during a period of 360 days since the vaccine became available. A clear pattern is visible; at each point in time, there is a positive monotonic relationship between cognitive ability and vaccination rate. For example, a vaccination rate of 80% is reached after approximately 50 days in the group with the highest cognitive ability score and after 180 days in the group with the lowest score. After 90 days, furthermore, the vaccination rate in the top group is 91% and only 71% in the lowest group. After 360 days, the vaccination rates have converged to 96% in the top group and 85% in the lowest group.

Panel B in Figure 1 displays coefficients estimates of cognitive ability, from model 1 without controls or mediators, with outcomes for being vaccinated within 90, 180, 270 and 360 days of availability. The leftmost bar shows that a one standard deviation increase in cognitive ability is associated with a 4.4 percentage point ($p<0.001$) increase in the likelihood of having taken the first dose within 90 days compared to a baseline rate of 84 percent. The following bars show that the pattern is similar for vaccination within 180, 270, and 360 days of availability, in that the estimates are positive (3.0, 2.5, and 2.4 percentage points) and statistically significantly different from zero ($p<0.001$, $p<0.001$, $p<0.001$). Detailed regression results are provided in Appendix Tables S4–S7. The overall pattern suggests that cognitive ability is a particularly important determinant of swift vaccination.

In Appendix Table S3, we show that the patterns are similar if we consider second dose vaccinations but also that the pattern is nearly identical for the 2,703 women who participated in the military enlistment process. We also show that the cognitive ability of fathers is positively associated with the vaccination of their children.

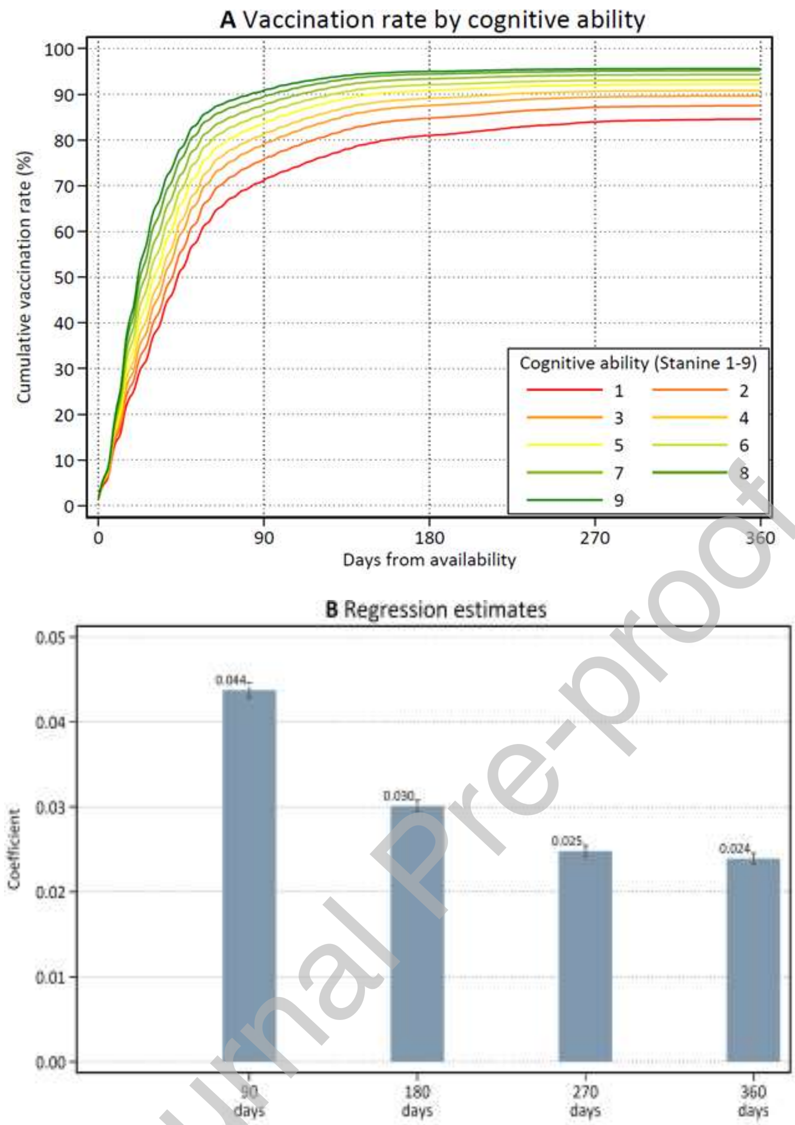

FIGURE 1. THE RELATIONSHIP BETWEEN COGNITIVE ABILITY AND TIMING OF COVID-19 VACCINATION. (**A**) Plot of the daily cumulative rate of first dose vaccinations by cognitive ability test score (stanine scale: min=1, max=9, mean=5, standard deviation=2) up until 360 days after the vaccine became available. Study population consists of all men having participated in the Swedish military enlistment process 1979–1997, N=750,381. (**B**) Regression-estimated coefficients of cognitive ability test score (mean=0, standard deviation=1) from bivariate OLS regressions with outcomes being indicators for first dose vaccination within 90, 180, 270, or 360 days of availability. Error bars represent 95% normal-based CIs (coefficient ± 1.96 SE) from OLS regressions with heteroscedasticity-robust standard errors. Study population consists of all men having participated in the Swedish military enlistment process 1979–1997, N=750,381. Detailed regression results are reported in Appendix Tables S4–S7.

Even though the pattern in Figure 1 shows a strong positive relationship between cognitive ability and vaccination, there is a concern that cognitive ability may be correlated with other factors also correlated with vaccination, meaning that the relationship may be spurious. We evaluate the importance of this concern by estimating versions of model 1. In this way, we account for mediating factors and control for a rich set of predetermined individual characteristics, including family background using a twin design. For this purpose, we focus the analysis on the sample of 3,375 twin pairs. The twin sample is remarkably similar to enlisted men at large in terms of socioeconomic characteristics, as well as in their vaccination behavior (see Appendix Table S1, Table S3, and Figure S2). In Figure 2, we show that the cognitive ability-vaccination gradient (at 90 and 360 days), in the twin sample is almost identical to that for men in general (0.043 vs. 0.044, 0.026 vs. 0.024).

The following regression estimates in Figure 2 display the coefficient estimate on cognitive ability when we control for the set of control variables and mediators discussed in Section II.A one at the time and, finally, in a model containing all at the same time. The figure contains two panels showing results regarding vaccination within 90 and 360 days respectively. Detailed regression results, including results for vaccination within 180 and 270 days, are reported in Appendix Tables S8–S11.

The overall pattern from the analysis is that the relationship between cognitive ability and vaccination is reduced but that it remains quantitatively and statistically significant in all specifications.[6] Controlling for personality and twin fixed effects has the largest impact on the estimates, suggesting that controlling for these confounders is indeed important. Regarding the mediators, we see that controlling for education reduces the relationship by about 30 percent, while the other mediators reduce the estimate less (5-27%). Taken together this suggest that only a smaller part of the effect is mediated through education, income, and the family variables.

[6] This pattern is also evident for the full population of enlisted men, see Appendix Tables S4–S7.

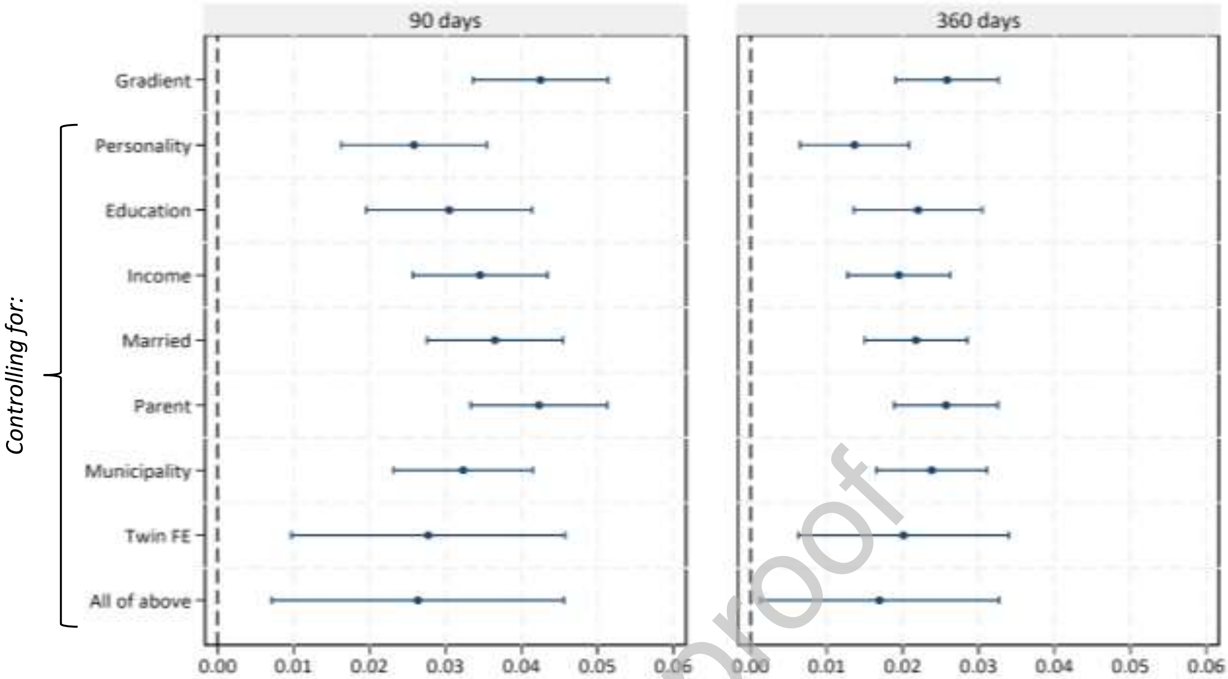

FIGURE 2. HOW THE RELATIONSHIP BETWEEN COGNITIVE ABILITY AND TIMING OF COVID-19 VACCINATION CHANGES WHEN ACCOUNTING FOR CONFOUNDING AND MEDIATING FACTORS. Regression-estimated coefficients of cognitive ability test score (mean=0, standard deviation=1) from OLS regressions with outcomes being indicators for first dose vaccination within 90 or 360 days of availability. The first row (Gradient) display the coefficient estimate of cognitive ability from a bivariate model. The rows: Personality, Education, Income, Married, Parent, Municipality, and Twin FE, show the coefficient estimate for cognitive ability from multivariate models when these factors are accounted for separately. The last row (All of above) displays the coefficient estimate of cognitive ability from a multivariate model with all the above factors being accounted for jointly. Error bars represent 95% normal-based CIs (coefficient ± 1.96 SE) from OLS regressions with heteroscedasticity-robust standard errors (rows 1-7) and standard errors clustered at twin pair level (rows 8 and 9). Study population consists of all twins having participated in the Swedish military enlistment process 1979–1997, N=6,750 (3,375 twin-pairs). Detailed regression results are reported in Appendix Tables S8–S11.

B. *Pre-booked appointments speed up and increase vaccination rates, particularly among low cognitive ability individuals*

The vaccinations have been administered by Sweden's 21 regional health care authorities (see Appendix section 1). At the time of the rollout of the vaccination program, Uppsala was the only health care region in Sweden to send out letters with pre-booked vaccination appointments to its residents aged 50 and above. Recipients could still choose not to take the vaccine by canceling the appointment or simply not showing up (both free of charge). The letter could thus be seen as a nudge turning the vaccination program from an opt-in into an opt-out program. Pre-booked appointments simplify the vaccination decision, as it signals that it is "good" to take the vaccine while also removing any barriers associated with booking an appointment. If complexity is the reason why individuals with lower cognitive abilities postpone their vaccination, we would expect this policy to boost vaccination rates disproportionately more for individuals with lower cognitive abilities. Changing the default option in this way has been shown to effectively change behavior in the intended way in a wide range of contexts (Madrian and Shea 2001; Li, Hawley, and Schnier 2013; Schultz et al. 2007; Brewer et al. 2016), including COVID-19 vaccination (Liu, Zhao, and Zheng 2022; Bonander, Ekman, and Jakobsson 2022; Patel et al. 2022).

Individuals of the same age cohorts living in other regions in Sweden were not assigned pre-booked appointments but had to book their appointments themselves. This regional variation in policy allows for an evaluation of the effect of pre-booked appointments by comparing the vaccination behavior of individuals aged 50–59 in Uppsala with that of a control group of same-age individuals living in other regions. This method has been used previously to show that pre-booked vaccination appointments for individuals aged 16–17 increased average vaccination rates (Bonander, Ekman, and Jakobsson 2022).

Panel A in Figure 3 presents the daily cumulative rate of first doses by cognitive ability test scores among individuals aged 50–59 in Uppsala, while the corresponding rates for the rest of the country are presented in panel B. It is evident that vaccination rates reached a high level much faster in Uppsala than in the rest of the country. It is also clear that the disparities with respect to cognitive ability are much smaller in Uppsala compared to the rest of Sweden. After 90 days, vaccination rates among individuals with the lowest cognitive ability score in Uppsala reached 90%, a level not reached after one year in the rest of the country and which is comparable to the vaccination rate for the individuals with the highest cognitive ability score in all of Sweden (see Figure 1).

Panel C illustrates the impact of the policy, measured as the difference between the graphs in panels A and B. During the first weeks, the vaccination rate was slower in Uppsala, which may be explained by fewer vaccinations per day due to cancellations, which is a natural consequence of pre-booked appointments. However, the vaccination rates in Uppsala increase rapidly and quickly outpace the rest of the country for all levels of cognitive ability; on average by 10.2 ($p<0.001$), 3.4 ($p<0.001$), 2.7 ($p<0.001$), 2.5 ($p<0.001$) percentage points after 90, 180, 270, and 360 days, respectively (see Appendix Table S12). Importantly, however, we also see that the policy disproportionately increased vaccination rates more among those with a lower cognitive ability and that this effect remains throughout the study period.

Panel D provides regression estimates showing how the policy increased the likelihood of having taken the first dose within 90 days by cognitive ability. The top-left estimate shows that pre-booked appointments increased the vaccination rate for individuals with the lowest cognitive ability score by 12.5 percentage points ($p<0.001$) more than for those with the highest score. The estimates decrease as cognitive ability increases, suggesting that the policy had a greater positive impact on vaccination rates the lower the cognitive ability.

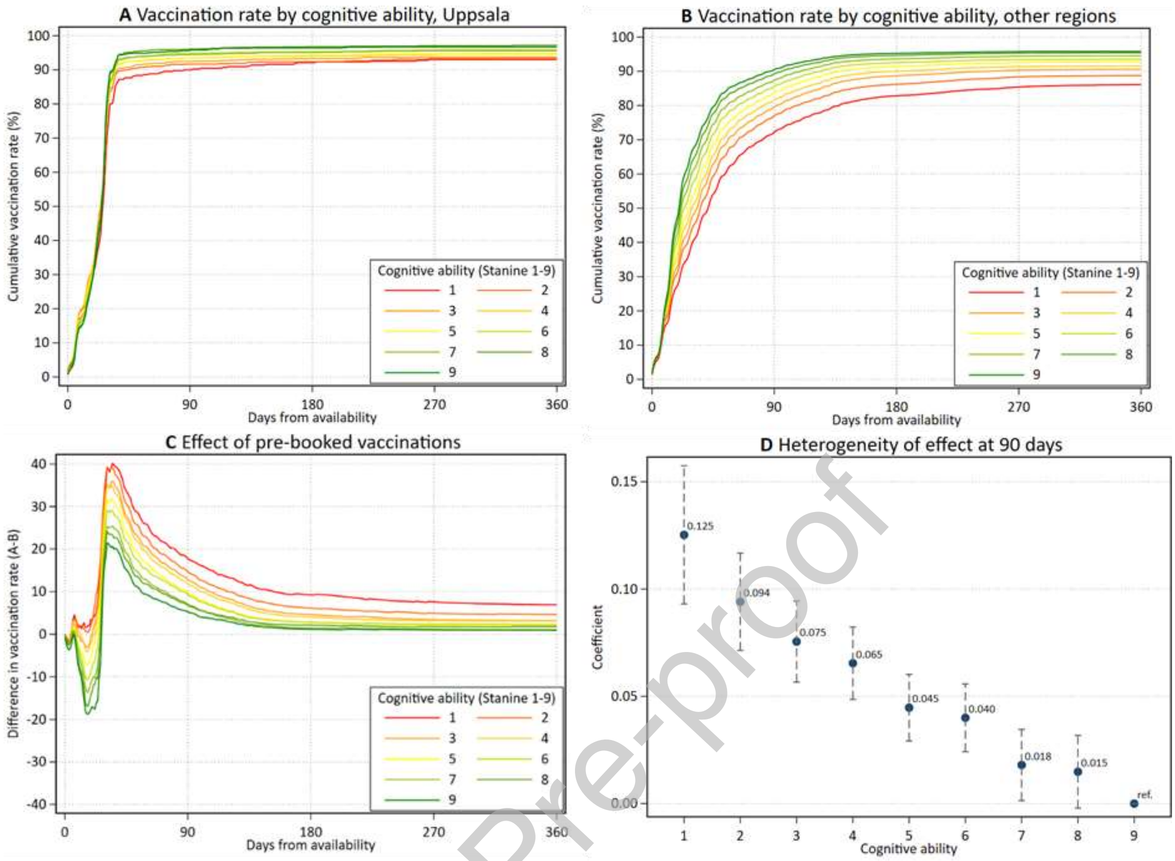

FIGURE 3. IMPACT OF PRE-BOOKED VACCINATIONS APPOINTMENTS ON COVID-19 VACCINATIONS. (**A** and **B**) Plot of the daily cumulative rate of first dose vaccinations by cognitive ability test score (stanine scale: min=1, max=9, mean=5, standard deviation=2) for a period of 360 days since the vaccine became available for all enlisted men aged 50–59 living in Uppsala, N=16,337 (**A**) and all enlisted men aged 50–59 living in regions other than Uppsala, N=449,377 (**B**). (**C**) Plot of the impact of pre-booked vaccination appointments by cognitive ability test score, measured as the difference between plots in (**A**) and (**B**). (**D**) Regression-based estimates of the impact of pre-booked vaccination appointments obtained from the following model: $y_i = \alpha + \beta Uppsala_i + \gamma \boldsymbol{Cognitive_i} + \partial Uppsala_i \times \boldsymbol{Cognitive_i} + \varepsilon_i$, where y_i is the outcome (vaccination of first dose within 90 days after the vaccine became available) of individual i. $Uppsala_i$ is an indicator variable taking the value one if the individual lived in Region Uppsala at the time of the vaccine roll-out, and thus received a pre-booked vaccination appointment, and zero if the individual lived in any of the other Swedish regions. $\boldsymbol{Cognitive_i}$ is a vector of indicator variables for the individuals' cognitive ability test score (stanine scale, 1–9), with the highest score (9) being the omitted category. $Uppsala_i \times \boldsymbol{Cognitive_i}$ is an interaction term between the variables described above, and the coefficients ∂, which are displayed in the graph, capture the impact of the policy for each cognitive ability score relative to the highest score. Finally, ε_i is an error term. Error bars represent 95% normal-based CIs (coefficient ± 1.96 SE) from OLS regressions with heteroscedasticity-robust standard errors. N=465,714 individuals. Detailed regression results are reported in Appendix Table S12.

IV. Conclusion

The results of this study offer support for the hypothesis that cognitive ability is a profound and direct determinant of COVID-19 vaccination. While it does not necessarily imply that the relationship is causal, we may at least confidently conclude that the relationship is not easily explained by family background, environment or socioeconomic factors.

Although cognitive ability is not directly observable by policy-makers, and while policies directly targeting individuals with certain levels of cognitive abilities may not be ethically or politically feasible, we have demonstrated that simplifying the vaccination decision through the use of pre-booked appointments was particularly effective in overcoming vaccination resistance and hesitancy among individuals with lower cognitive abilities. Given that these individuals are relatively more susceptible to various health risks (Deary et al. 2021), including COVID-19 infection (Batty, Deary, and Gale 2021), such a policy may lead to significant welfare gains for this group. Our findings also imply that if everyone were vaccinated as swiftly as individuals with a high cognitive ability, the pandemic would likely have ended earlier, with fewer lives lost and with lower costs for society (Kominers and Tabarrok 2022).

Some limitations are nevertheless important to note. First, our focus has been on individuals aged 42–59, who are in the mid-range in terms of risk of suffering severe health consequences from COVID-19 infection (Williamson et al. 2020). Consequently, we cannot say whether the results generalize to older individuals, who face a higher risk, or to younger individuals, who face a lower risk of severe COVID-19 infection. Second, most of our results are based on men, but the fact that we observe a nearly identical relationship for the smaller sample of women indicates that cognitive ability constitutes an important determinant for women as well. Third, our results are based on individuals in Sweden, but the fact that a similar positive relationship between cognitive ability and attitudes towards vaccination has been found in other countries (Murphy et al. 2021; Batty et al. 2021) suggests that they might reflect a more general relationship. Finally, the fact that we study COVID-19 vaccinations makes it difficult to say to what extent our results generalize to other future infections and vaccines, which may cause more or less severe infections and get more or less public attention. Nevertheless, recognizing that cognitive ability and the complexities of the vaccination decision influence vaccination behavior can prove valuable in the design of diverse vaccination programs.

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Author Statement

All authors have participated in the conception and design of the study, acquisition of the data, data analysis, interpretation, writing of the manuscript, revising the manuscript, and approving the manuscript. Finally, all authors take public responsibility for the content.

The authors declare that they have no relevant or material financial interests that relate to the research described in this paper.