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Promoting RAPID Vaccine Science Education at the Onset of the COVID-19 Pandemic

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At the onset of the 2019 coronavirus disease (COVID-19) pandemic, it was clear that we needed to support public education on the science of vaccines. This project was born of that need and led to the development of comprehensive educational materials that addressed the process of science, severe acute respiratory syndrome coronavirus 2 biology, vaccine development, and science communication and outreach. Called the "Online Vaccine Science Resources for COVID-19 Education," the materials generated were designed to be implemented by educators and community groups in various contexts. They took the form of four modules and general audience informational videos available on a YouTube channel. Each module was assembled as a toolkit with instructional videos, assessments, discussion questions, assignments, synthesis activities, and guides for constructing infographics and dual poster (science and general public audience) presentations. The materials were piloted and tested in various educational settings, including 2-year and 4-year colleges. Data gathered from surveys of faculty and student participants suggested that exposure to the materials promoted student trust in vaccination and the scientific process of vaccine development, and increased the likelihood of their getting a freely available vaccine. Assessment data indicated that the materials were successful in helping students achieve the learning objectives for the modules. Our results underscored the continued need for science education strategies that address the critical problem of vaccine hesitancy as we continue to emerge from the COVID-19 pandemic.

KEYWORDS vaccine, SARS-CoV-2, scientific literacy, vaccine hesitancy, public education, misinformation, online, science communication

INTRODUCTION

As we watch in early 2023 the ongoing efforts to vaccinate populations and develop additional doses (boosters) aimed at combating the emergence of variants of concern of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) virus, we can reflect on how much we have achieved since the beginning of the pandemic. But early in 2020, the need to develop and widely distribute an effective SARS-CoV-2 vaccine was recognized as a critically important milestone to achieve, with many technological, social, cultural, and economic barriers to overcome. Unfortunately, one of the most pressing barriers was vaccine hesitancy. A poll in mid-May indicated that as few as 50% of people in the United States were committed to receiving a vaccine, with 25% unsure (1). Moreover, inequities in vaccine hesitancy were illuminated; for example, 37% of Hispanic participants indicated that they were not sure about getting vaccinated, and 23% said they would not get vaccinated, compared to white participants, of which

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56% indicated they would get the vaccine and 31% were not sure (1). A survey in late April 2020 by the Pew Research Center found 31% of adults who were millennials or younger said they would probably or definitely not get vaccinated (2). These results were subsequently backed by surveys from Gallup and the Associated Press-NORC Center for Public Affairs Research (3, 4). In these surveys, 35% of 18 to 29 year olds, an age group that included most college students, said they would not get vaccinated and 22% were not sure. The percentage of young adults saying they would not get vaccinated was the largest of any age group in the poll, almost double the 18% of 30 to 44 year olds and the 20% of 45 to 59 year olds. These survey results indicated a pressing need to connect with the community regarding vaccinations for 2019 coronavirus disease (COVID-19) and to respond to vaccine hesitancy.

At the time, we considered that a lack of scientific knowledge and literacy might be at the core of much of the vaccine hesitancy we were observing. Vaccine hesitancy existed long before the onset of the COVID-19 pandemic (5). It is defined by the WHO as a "delay in acceptance or refusal of vaccines despite availability of vaccination services" (6). A study from France that surveyed people in July 2020 revealed several factors significantly associated with outright vaccine refusal and vaccine hesitancy, including female gender, age, lower educational level, and poor compliance with recommended vaccinations in the past (7). Another study surveying people from the United States and the United Kingdom demonstrated that despite an understanding of the mode of transmission and symptoms associated with the virus, many respondents held misconceptions regarding effective ways to prevent infection, including a belief in falsehoods that were disseminated on social media (8). A pair of randomized control trials involving expectant women demonstrated that adherence to the immunization schedule could be improved by a single prenatal education session, and benefits were evident from stepwise education interventions that were offered prenatally, postnatally, and 1 month after birth (9, 10). An educational intervention campaign about the measles vaccine in the Philippines was shown to significantly impact the vaccine knowledge of the parents of high school children (11). In summary, ample evidence pre-COVID suggested that exposure to accurate information about vaccines and their development at multiple stages of life was a critical and shared responsibility (12).

We recognized that institutions of higher education had both the opportunity and obligation to respond to the sentiments being demonstrated in these surveys, as well as to the antiscience social media messaging, misconceptions, and misinformation that were prevalent early in the COVID-19 pandemic (13). We also recognized that even if an effective vaccine was developed, its deployment would not be successful if individuals declined to be vaccinated, particularly if their hesitancy was due to deficits in vaccine and science knowledge, a lack of trust in the scientific process, or a limited understanding of credible sources of scientific information.

At the time, many factors were contributing to the distrust of emerging vaccines, including the apparent speed with which they were being developed, the perception that they were experimental (and thus perceived as risky), and the lack of long-term safety data. To combat the lack of scientific knowledge and literacy, as well as the mistrust of COVID-19 vaccines, and to connect with diverse communities in need of vaccination (particularly minority communities and young individuals), we engaged in our core work as educators with the aim of producing informational materials on COVID-19 in the form of videos and workshops and the dissemination of the materials widely to faculty at colleges and universities. Our materials were implemented in a variety of institutional contexts, and we used pre- and post-activity surveys to determine if exposure to our curricular material would positively influence students' perceptions of vaccines across different demographic, gender, and age groupings. We anticipated that having completed the modules, which were designed to improve their understanding of the scientific process, COVID-19, vaccine science, and scientific communication, students' beliefs in vaccine safety and their usefulness to combat infectious disease would increase, their trust in the scientific process of vaccine development would improve, and they would ultimately choose to get the vaccine, the ultimate test of our materials.

Intended audience

Our educational materials were designed for a broad range of audiences, including undergraduates in general education and introductory science courses, undergraduates in science and nonscience major courses that focused on COVID-19, and the general public through community organizations and informal science education centers and museums. For this reason, only a basic understanding of science at the high school level is sufficient for understanding the module materials. The overall project was designed to introduce each audience to the process of science and then to scaffold the learning from exploring the SARS-CoV-2 virus itself to vaccines and vaccine production, and then to communicating science and responding to vaccine hesitancy.

Learning time

As student audiences can vary widely in their prior knowledge and preparation, the materials were designed to gradually expose them to the concepts according to the schedule of the student or faculty member. All materials are available online both as recordings and as PowerPoint slides, adaptable to the instructors and their schedules. The module videos range in length from 30 to 95 min, with the entire set of videos taking about 4.25 h to watch. Three of the four modules are in multiple parts. Owing to the online nature of the materials, the length of time that would be taken to complete the modules is variable, and an instructor can choose to use one or all of the modules and assessments provided, depending on the learning context.

TABLE 1
The four modules of OVSR and the topics covered

Module no.	Module title	Topics
1	Framing COVID-19 Vaccination through an Understanding of Science	The process of scientific investigation, the language of science, the power and limitations of science, tentative nature of science
2	COVID-19 Science	Viral structure of SARS-CoV-2, coronavirus replication, PCR and antigen testing for SARS-CoV-2 infection
3	Vaccine Science	History of vaccine development, immune recognition of vaccines, herd immunity, vaccination protocols and clinical trials, history of antivaccine movements, racial and ethnic disparities and inequalities in immunization coverage, status of COVID-19 vaccination protocol
4	COVID-19 Vaccination Communication	COVID-19 vaccine mis- and disinformation, vaccine hesitancy, proven effective methods of communication among different groups

Prerequisite student knowledge

A basic understanding of science (high school level) would be sufficient.

Learning objectives

Each one of the modules was designed to both stand alone and to work in succession to promote the understanding of science, the virus, vaccines, and science communication, and each of the modules has its own learning objectives. The objectives for module 2 (COVID-19 Science) are as follows:

2a) Identify the virus that causes COVID-19
2b) Characterize the components of SARS-CoV-2
2c) Describe the process by which SARS-CoV-2 infects a human cell
2d) Distinguish between different types of SARS-CoV-2 tests

The learning objectives for module 3 (Vaccine Science) are as follows:

3a) Describe the basic science of immunity and vaccine activity
3b) Interpret emerging information on COVID-19 vaccine development and distribution
3c) Discuss the benefits, risks, and priorities for vaccination

We present the findings we observed for implementation of modules 2 and 3, for which we had institutional review board (IRB) approval. Additional learning objectives for the remaining modules can be found in Table S1 of the supplemental material.

PROCEDURE

Material development

Since the goal of the Online Vaccine Science Resources (OVSR) project was to produce versatile, accessible resources for a broad range of audiences during the pandemic, the resources were designed for online dissemination and delivery. Specifically, four COVID-19 modules were produced, each of which included materials for asynchronous delivery and resources for interactive synchronous delivery and active learning. Each module contained 1 to 5 instructional videos (21 videos overall) for asynchronous viewing on YouTube. Synchronous resources included topic reviews and assessments, discussion and reflection questions, and synthesis activities, such as infographic creation, case study analysis, and poster presentations. The four modules together could comprise a general education course, the modules could be integrated individually into an existing course, or material on a single topic could be used independently. The four OVSR modules are shown in Table 1. Module 1 was designed to introduce students to the process of science and by doing so help develop their general scientific literacy, which we define as the knowledge and understanding of scientific concepts and processes required for personal decision-making, participation in civic and cultural affairs, and economic productivity (14, 15). The remaining modules were focused on science in the context of SARS-CoV-2, vaccine development, and vaccination communication (Table 1). We hoped that these modules would help reinforce students' understanding of the scientific process through its contextualization to COVID-19 and help improve the likelihood of their accepting the value of vaccines.

The materials were produced in Summer and Fall 2020 and were piloted in a freshman-level Life Science biology majors class at Worcester Polytechnic Institute, with approximately 65 students enrolled. The modular form of the educational materials lent itself to the supplementation of faculty lectures with videos. The activities were also used as a form of reinforcement for the research process. Additional small groups of undergraduates and community partners also provided early feedback. Module materials were ready for initial dissemination in Spring 2021. OVSR instructional videos were initially created in English, while the adaptation of the educational materials for use in specific indigenous communities is ongoing. The materials are available online at https://www.vaccine-science-education.org, and the YouTube channel with options to view the captions in multiple languages is at https://www.youtube.com/channel/UC8tJF3aOIDlRcrnwNymy46w.

Student instructions

Each of the modules was designed to be delivered in both asynchronous and synchronous modalities, in person and online. Transcripts of the videos are provided as well. Students can view and pause the videos and complete the assignments as they are going through the modules on their own time or view them in class by integrating them into the learning management systems provided by the instructors. Additional student instructions for each module are available on the project website (https://www.vaccine-science-education.org/) and QUBES project site (https://qubeshub.org/community/projects/onlinevaccination/publications). These instructions are also found in the supplemental material.

Faculty instructions

Each of the modules has associated suggested assignments and assessments that can be used according to the needs and expectations of the instructor. In addition, an outline of each module is provided to the instructor. Additional faculty instructions for each module are available on the project website (https://www.vaccine-science-education.org/) and QUBES project site (https://qubeshub.org/community/projects/onlinevaccination/publications). These instructions are also found in the supplemental material.

Suggestions for determining student learning

As each of the modules has clearly defined learning outcomes, student learning can be measured in a variety of ways. The lab activities of module 2 are suited to questions in data sheets, and the lectures of module 4 are suited to reflections and discussion board activities. Additional ideas include the development of infographics and a dual poster activity. While these activities help assess student learning for each of the instructional modules, our goal was also to determine whether the students' perceptions of vaccine science changed. To test this, we used surveys that were administered via an online system.

Sample data

Sample data are provided in the "Evidence of student learning" section of the Discussion.

Safety issues

There are no safety concerns associated with this activity. Santa Clara University's IRB reviewed the activities (including the activities performed at New York University) and declared our study exempt. The activities at Worcester Polytechnic University (WPI) were also approved by the WPI IRB.

DISCUSSION

Field testing

In the spring of 2021, Karen Oates, co-Principal Investigator on the project, created a QUBES faculty mentoring network (FMN) for testing and dissemination of the modules the team was developing. QUBES is a product of the Quantitative Undergraduate Biology Education and Synthesis (qubeshub.org) project. The FMN was called "COVID Vaccination: from Science to Society" and consisted of 16 members from various institutions teaching a variety of introductory and advanced biology courses (Table S2). The FMN met biweekly via Zoom for the period from January to May 2021. Module authors made presentations of the materials they were developing, followed by question-and-answer sessions and general feedback among participants. The FMN members agreed to adopt at least two modules in their teaching for the Spring 2021 semester or quarter.

After implementing the materials in their courses, the FMN participants were surveyed to obtain their evaluations of the modules. The survey questions for FMN participants focused on module usability and like or dislike. Most items on the survey had a 7-point Likert scale (with 1 = strongly disagree, 2 = moderately disagree, 3 = somewhat disagree, 4 = neither agree nor disagree, 5 = somewhat agree, 6 = moderately agree, and 7 = strongly agree). The items on the faculty survey are listed in Table 2, along with the six responses (37.5%) from the total group. The following table includes the data from the seven overall questions. Given the low number of respondents, it was not possible to make broad conclusions about these responses. However, it appears that the faculty generally had positive reactions to using the module resources, with the highest response being found for the question of whether they would encourage their colleagues to use the materials.

Evidence of student learning

As the goal of the materials was to promote an understanding of vaccine science, we administered surveys to the students who experienced the educational modules in their courses. The surveys were designed to be simple and focused on addressing vaccine hesitancy. Demographic information was also collected for the students so that responses could be disaggregated for analysis. The surveys were completed both pre- and post-instruction in the courses led by the FMN participants and were administered through a link that instructors included in their learning management systems. To avoid IRB complications (given the variety of campuses involved, etc.), no identifiable data were collected, meaning that the data are unpaired. The students who responded to the preinstruction survey may not have been the same individuals who responded to the postinstruction survey. The items on the survey had a 7-

TABLE 2
FMN participant responses to the survey (n = 6)

Statement	Avg response (scale of 1–7)
The toolkits were a valuable resource for my teaching.	6.67
The material presented in the toolkits was factually correct.	6.67
The material presented in the toolkits was thought-provoking.	6.33
The toolkits were easy to use.	6.67
My students/participants appeared to be engaged with the materials.	6.00
I plan to use these toolkits in my future courses or educational programs.	6.60
I would encourage a colleague to use these materials.	6.83

point Likert scale (1 = strongly disagree, 2 = moderately disagree, 3 = somewhat disagree, 4 = neither agree nor disagree, 5 = somewhat agree, 6 = moderately agree, and 7 = strongly agree). The three items included in the student survey were as follows:

1. Vaccines are a safe and effective means of combating infectious diseases.
2. I trust the scientific processes used in the development of vaccines.
3. I will get the COVID-19 vaccine if it is offered free of charge.

These statements align with the learning outcomes for module 3, in particular objectives 3b, which deals with interpreting emerging information on COVID-19 vaccine development and distribution, and 3c, which involves discussing the benefits, risks, and priorities for vaccination. While each of the modules stands alone, these learning outcomes would build upon the learning outcomes of module 1 (Framing COVID-19 Vaccination through an Understanding of Science) and module 2 (COVID-19 Science) and culminate with module 4 (COVID-19 Vaccine Communication). All the learning outcomes are outlined in the Table S1 in the supplemental material. Table 3 summarizes the responses.

The pre- and post-instruction averages had statistically significant increases in the areas considering that vaccines are safe and effective, trust in science, and the likelihood of getting vaccinated. The largest increase was seen in the likelihood of getting vaccinated. These were promising results for overcoming vaccine hesitancy. Tables showing the above data disaggregated by institution, gender, age, and race are shown in the supplemental material (Tables S3 to S7). When looking at differences in student responses based on gender, we found women to have a statistically significant increase in all three survey responses. Men's responses also increased across all questions, but there were not enough male respondents to ensure these were generalizable findings. When breaking the sample down by age, we saw that no particular group had statistically significant increases to the first question about whether or not vaccines are safe and effective. The second and third questions had statistically significant increases in the 18- to 22-year-old age categories. When we looked at data disaggregated by race, we saw some statistically significant increases, with Hispanic students showing increases to questions 2 and 3, African American students showing increases to question 1, and Asian students showing increases to question 2. We also had responses from non-white students, who were from groups too small enough to disaggregate further. When combining all non-white students, we saw large increases for all three questions, in comparison to their white counterparts who only had an increase for question 2.

Evidence of student learning through question-based assessment of content

In Fall 2022, we performed a course-based evaluation of student learning using one instructional video from module 2, COVID-19 Science. This video had the following learning objectives: 2a, identify the virus that causes COVID-19; 2b,

TABLE 3
Student survey responses from courses taught by faculty using module materials

Statement	Learning objective	Mean ± SD response value[a] (n)	
		Pretest	Posttest
Vaccines are a safe and effective means of combating infectious diseases.	3c	6.36 ± 1.04 (356)	6.56 ± 0.84* (163)
I trust the scientific processes used in the development of vaccines.	3b	6.15 ± 1.11 (353)	6.56 ± 0.85*** (160)
I will get the COVID-19 vaccine if it is offered free of charge.	3c	6.21 ± 1.52 (354)	6.61 ± 1.06*** (161)

[a]Scores were on a Likert scale from 1 to 7. Statistically significant differences (by t test with Excel) for pre- versus post-test data are denoted by asterisks: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

TABLE 4
Comparison of pre- and post-test responses to measure student learning from watching the module 2 instructional video

Question	Learning objective	Pretest mean ± SD (*n* = 106)	Posttest mean ± SD (*n* = 108)	Pre vs post difference in means	Significance
1. What type of virus causes COVID-19?	2a	0.9717 ± 0.1666	0.9815 ± 0.1354	0.0009	$P > 0.05$
2. What type of biological molecule is the genome of the virus composed of?	2b	0.87735 ± 0.32958	0.9815 ± 0.1354	0.1041	$P < 0.01$
3. What part of the virus is used to attach to a human cell?	2c	0.5660 ± 0.4979	0.8796 ± 0.3269	0.3136	$P < 0.001$
4. When the virus attaches to a human cell, what protein receptor does it use?	2c	0.4057 ± 0.4936	0.7778 ± 0.4176	0.3721	$P < 0.001$
5. What type of COVID-19 test detects the presence of viral genes?	2d	0.7170 ± 0.4526	0.8703 ± 0.3375	0.1534	$P < 0.01$
6. A rapid antigen test detects fragments of which type of viral molecule?	2d	0.4906 ± 0.5023	0.8611 ± 0.3474	0.3705	$P < 0.001$
Total score		4.028 ± 1.150	5.352 ± 0.9503	1.3236	$P < 0.001$

characterize the components of SARS-CoV-2; 2c, describe the process by which SARS-CoV-2 infects a human cell; and 2d, distinguish between different types of SARS-CoV-2 tests.

This video was used in a nonmajors science course entitled Molecules of Life, with an enrollment of 119 students. An anonymous online pretest containing six multiple-choice items was administered during a class period before any discussion of COVID-19 science. The test questions avoided the use of technical language about SARS-CoV-2 so that the pretest could be a reliable measure of students' prior knowledge. Students were then asked to watch the instructional video, and an anonymous online posttest was administered in a class period 2 days later using the same questions with a randomized answer order. A total of 106 students completed the pretest, and 108 students completed the posttest, for response rates of 89.07% and 90.76%, respectively. During this 2-day period, the instructional video had a total of 141 additional views, which suggests that some students watched the video more than once.

The results of a pre-test versus post-test analysis are provided in Table 4. Students were assigned 1 point for a correct answer and 0 points for an incorrect answer. The table contains the mean scores and standard deviations for the pretest and posttest, together with pre- versus post-instruction differentials and statistical significance based on a two-tailed, unpaired *t* test using Excel. A complete list of test questions and multiple-choice answers is provided in Table S8. The results in Table 4 indicate that only one of the questions ("What type of virus causes COVID-19?") did not show a statistically significant difference in response accuracy between the posttest and pretest. By this point in the COVID-19 pandemic, when students had been exposed to the word "coronavirus" for over 2 years, this information had become common knowledge. However, the responses to the remaining five questions all demonstrated student learning gains that were statistically significant, with large gains for questions 3, 4, and 6. In addition, the gain in total scores from the pretest to the posttest showed a statistical significance level of $P < 0.001$. These results emphasize the continued utility of the materials to promote understanding of COVID-19 science for nonmajors.

In Spring 2023, we performed a course-based evaluation of student learning using one instructional video from module 3, Vaccine Science. This video had the following learning objectives: 3a, describe the basic science of immunity and vaccine activity; 3b, interpret emerging information on COVID-19 vaccine development and distribution; and 3c, discuss the benefits, risks, and priorities for vaccination. The video was used in a nonmajors science course entitled Human Biology, with an enrollment of 52 students. An anonymous online pretest containing seven multiple-choice items was administered during a class period before any discussion of COVID-19 vaccines. Students were then asked to watch the instructional video, and an anonymous online posttest was administered on the same day using the same

TABLE 5
Comparison of pre- and post-tests to measure student learning from watching the module 3 vaccine science video

Statement	Learning objective	Pretest (*n* = 52)		Posttest (*n* = 51)	
		No. of students answering correctly	% of total	No. of students answering correctly	% of total
1. Modern technologies produce vaccines that: a. Suppress immune responses and can replicate b. Suppress immune responses and cannot replicate c. Stimulate immune responses and can replicate d. Stimulate immune responses and cannot replicate	3a	22	42%	39	76%
2. Vaccination promotes the development of: a. Innate immunity b. Natural immunity c. Adaptive immunity d. Primary immunity	3a	43	83%	43	84%
3. What is the main benefit of vaccination with respect to individual health? a. Vaccination prevents individuals from having disease symptoms b. Vaccination leads to protective immunity with a lower risk of severe symptoms c. Vaccination promotes stronger immune protection than exposure to live pathogen d. Vaccines are quick and nonspecific ways to protect individuals from disease	3c	44	85%	48	94%
4. A vaccine formulation containing lipid nanoparticles is probably a: a. Nucleic acid vaccine b. Conventional vaccine c. Live attenuated vaccine d. Vector-based vaccine	3b	29	56%	39	76%
5. Questions about vaccine dosing and effectiveness in the general population are addressed in: a. Preclinical studies b. Phase I clinical trials c. Phase II clinical trials d. Phase III clinical trials	3b	17	33%	33	65%
6. Which of the following statements about immunity is correct? a. Once you are exposed to a pathogen, you are immune to it. b. Protective immunity is developed after secondary exposure to a pathogen. c. Most people will make identical antibodies in response to the same pathogen. d. Herd immunity requires all members of a population to be exposed to a pathogen at least once.	3a	29	56%	39	76%

(Continued on next page)

TABLE 5 (Continued)

Statement	Learning objective	Pretest (*n* = 52)		Posttest (*n* = 51)	
		No. of students answering correctly	% of total	No. of students answering correctly	% of total
7. Multiple vaccinations and boosters are important because: a. Vaccine components are broken down in the body over time. b. As cells die off, the immune system "forgets" what it was exposed to. c. Vaccine formulations must be updated as pathogens evolve. d. Most people do not mount an immune response to their first vaccination.	3c	33	63%	29	57%

questions with a randomized answer order. A total of 52 students completed the pretest and 51 students completed the posttest, for response rates of 100% and 98%, respectively. The results of a pretest versus posttest analysis are provided in Table 5.

In most cases, the number of students answering the questions correctly increased. We noted that for question 2, the respondents were able to answer this question correctly both before and after watching the module. In the case of question 7, however, the respondents chose the wrong answer more frequently postexposure to the module. This finding serves to emphasize the need for formative and frequent assessments of student understanding as we progress throughout a semester and the likely need for the students to complete all the modules in the series to reinforce their understanding of COVID-19, SARS-CoV-2, and vaccine science.

Overall, our results point to the modules increasing student understanding of vaccines and the notion that they are safe and effective. We consider that these modules helped students to understand the scientific process and increased the likelihood of their becoming vaccinated after going through this curriculum, though we have several examples of possible gaps in conceptual understanding that still need further support. These are significant results for the project's overall goals and are promising when looking to decrease vaccine hesitancy. We cannot rule out the possibility that students who were not exposed to our curriculum would have shown similarly positive perceptions regarding the vaccine. Many studies have deliberated over the reasons for vaccine hesitancy (16, 17). Several recent studies have more concretely made the connection between scientific literacy and vaccine hesitancy during the COVID-19 pandemic (17–19). In particular, education levels have been shown to be a contributing factor, with those attaining higher levels of education showing a decrease in vaccine refusal or hesitancy (7, 20, 21). Keselman and colleagues (22) found that, "It is likely that information literacy and science literacy influenced public health trust and positive attitudes toward science, mediating their impact on positive attitude toward vaccination." Separately, Biasio (23) suggested that, "Obstacles to vaccination might be overcome by improving health education, especially when targeted, not only at parents and adult populations but also at students, starting from primary and secondary schools, as recently suggested." There are some studies that suggest the opposite trend. For example, a study from Thailand showed that increasing vaccine literacy among health care workers was not associated with vaccine acceptance (24). More work to promote scientific literacy and vaccine acceptance is warranted.

Our data, along with that of others, would seem to suggest that there is value in the continued exposure of the public to educational materials. Increasing the scientific literacy of the public and their capacity to discern trustworthy sources of information remains critical as we continue the development of additional bivalent doses (boosters) to respond to emerging variants of the SARS-CoV-2 virus.

Possible modifications

These materials were generated in the first years of the COVID-19 pandemic. Owing to the rapid development of COVID-19 science, several of our modules have already been updated to reflect the emergence of new variants, our changing knowledge with respect to vaccines and vaccine delivery, and our understanding of how we must continue to effectively communicate the need for additional doses (boosters). A more recent video has been uploaded to module 2 on the YouTube channel that addresses the science of COVID-19 variants; our more recent assessment data of a nonmajors course in Spring 2023 demonstrated that the materials continue to have value in promoting understanding of COVID-19 science. As we have provided the PowerPoint slides, the instructors can easily modify and update the materials as they go. We plan to update these modules regularly and add resources to our website to ensure that these materials will continue to be of value to educators to promote vaccine uptake and combat vaccine hesitancy.

SUPPLEMENTAL MATERIAL

Supplemental material is available online only.

SUPPLEMENTAL FILE 1, DOCX file, 0.2 MB.

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REFERENCES

1. Cornwall W. 2020. Just 50% of Americans plan to get a COVID-19 vaccine. Here's how to win over the rest. https://www.science.org/content/article/just-50-americans-plan-get-covid-19-vaccine-here-s-how-win-over-rest. Accessed 17 October 2022.
2. Murakami K. 2020. Should students be required to be vaccinated? https://www.insidehighered.com/news/2020/07/10/many-young-americans-wont-take-coronavirus-vaccine. Accessed 17 October 2022.
3. Neergard L, Fingerhit H. 2020. AP-NORC poll: half of Americans would get a COVID-19 vaccine. https://apnews.com/article/donald-trump-us-news-ap-top-news-politics-virus-outbreak-dacdc8bc428dd4df6511bfa259cfec44. Accessed 17 October 2022.
4. Mullen OS. 2020. One in three Americans would not get COVID-19 vaccine. https://news.gallup.com/poll/317018/one-three-americans-not-covid-vaccine.aspx. Accessed 20 October 2022.
5. Eddy JJ, Smith HA, Abrams JE. 2023. Historical lessons on vaccine hesitancy: smallpox, polio, and measles, and implications for COVID-19. Perspect Biol Med 66:145–159. https://doi.org/10.1353/pbm.2023.0008.
6. MacDonald NE, SAGE Working Group on Vaccine Hesitancy. 2015. Vaccine hesitancy: definition, scope and determinants. Vaccine 33:4161–4164. https://doi.org/10.1016/j.vaccine.2015.04.036.
7. Schwarzinger M, Watson V, Arwidson P, Alla F, Luchini S. 2021. COVID-19 vaccine hesitancy in a representative working-age population in France: a survey experiment based on vaccine characteristics. Lancet Public Health 6:e210–e221. https://doi.org/10.1016/S2468-2667(21)00012-8.
8. Geldsetzer P. 2020. Knowledge and perceptions of COVID-19 among the general public in the United States and the United Kingdom: a cross-sectional online survey. Ann Intern Med 173:157–160. https://doi.org/10.7326/M20-0912.
9. Saitoh A, Saitoh A, Sato I, Shinozaki T, Kamiya H, Nagata S. 2017. Effect of stepwise perinatal immunization education: a cluster-randomized controlled trial. Vaccine 35:1645–1651. https://doi.org/10.1016/j.vaccine.2017.01.069.
10. Hu Y, Chen Y, Wang Y, Song Q, Li Q. 2017. Prenatal vaccination education intervention improves both the mothers' knowledge and children's vaccination coverage: evidence from randomized controlled trial from eastern China. Hum Vaccin Immunother 13:1–8. https://doi.org/10.1080/21645515.2017.1285476.
11. Casiño JJ, Walag AMP. 2020. Design and development of a science literacy material on vaccination as an intervention campaign for parents of high school students in the Philippines. Am J Educ Res 8:762–766. https://doi.org/10.12691/education-8-10-4.
12. Biasio LR, Corsello G, Costantino C, Fara GM, Giammanco G, Signorelli C, Vecchio D, Vitale F. 2016. Communication about vaccination: a shared responsibility. Hum Vaccin Immunother 12:2984–2987. https://doi.org/10.1080/21645515.2016.1198456.
13. Loomba S, de Figueiredo A, Piatek SJ, de Graaf K, Larson HJ. 2021. Measuring the impact of COVID-19 vaccine misinformation on vaccination intent in the UK and USA. Nat Hum Behav 5:337–348. https://doi.org/10.1038/s41562-021-01056-1.
14. National Research Council. 1996. National science education standards. National Academies Press, Washington, DC. https://www.nap.edu/catalog/4962/national-science-education-standards. Accessed 9 December 2020.
15. Fernbach PM, Light N, Scott SE, Inbar Y, Rozin P. 2019. Extreme opponents of genetically modified foods know the least but think they know the most. Nat Hum Behav 3:251–256. https://doi.org/10.1038/s41562-018-0520-3.
16. Shah A, Coiado OC. 2023. COVID-19 vaccine and booster hesitation around the world: a literature review. Front Med 9. https://doi.org/10.3389/fmed.2022.1054557.
17. Cameron LD, Lawler S, Robbins-Hill A, Toor I, Brown PM. 2023. Political views, health literacy, and COVID-19 beliefs and behaviors: a moderated mediation model. Soc Sci Med 320:115672. https://doi.org/10.1016/j.socscimed.2023.115672.
18. Motoki K, Saito T, Takano Y. 2021. Scientific literacy linked to attitudes toward COVID-19 vaccinations: a pre-registered study. Front Commun 6. https://doi.org/10.3389/fcomm.2021.707391.
19. Dubé È, Ward JK, Verger P, MacDonald NE. 2021. Vaccine hesitancy, acceptance, and anti-vaccination: trends and future prospects for public health. Annu Rev Public Health 42:175–191. https://doi.org/10.1146/annurev-publhealth-090419-102240.
20. Petravić L, Arh R, Gabrovec T, Jazbec L, Rupčić N, Starešinič N, Zorman L, Pretnar A, Srakar A, Zwitter M, Slavec A. 2021. Factors affecting attitudes towards COVID-19 vaccination: an online survey in Slovenia. Vaccines 9:247. https://doi.org/10.3390/vaccines9030247.
21. Robertson E, Reeve KS, Niedzwiedz CL, Moore J, Blake M, Green M, Katikireddi SV, Benzeval MJ. 2021. Predictors of COVID-19

vaccine hesitancy in the UK household longitudinal study. Brain Behav Immun 94:41–50. https://doi.org/10.1016/j.bbi.2021.03.008.
22. Keselman A, Arnott Smith C, Wilson AJ, Leroy G, Kaufman DR. 2022. Cognitive and cultural factors that affect general vaccination and COVID-19 vaccination attitudes. Vaccines 11:94. https://doi.org/10.3390/vaccines11010094.
23. Biasio LR. 2017. Vaccine hesitancy and health literacy. Hum Vaccin Immunother 13:701–702. https://doi.org/10.1080/21645515.2016.1243633.
24. Siewchaisakul P, Sarakarn P, Nanthanangkul S, Longkul J, Boonchieng W, Wungrath J. 2022. Role of literacy, fear and hesitancy on acceptance of COVID-19 vaccine among village health volunteers in Thailand. PLoS One 17:e0270023. https://doi.org/10.1371/journal.pone.0270023.