Special Series: Scientific Literacy

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Primary Scientific Literature Is Not Just for Students and Academics: a Study of Primary Source Modalities and Predictors of Learning across Adulthood

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The 2019 coronavirus disease pandemic and distrust for popular media have highlighted the need for effective methods of direct communication of biomedical science to the public. It is presently unclear how well nonexperts can learn from primary scientific sources and what factors predict such learning in the general public. The present study examined three modalities for learning about biomedical science directly from study investigators: primary scientific articles, annotated primary scientific articles presented online with interactive learning features, and TEDTalks about scientific studies presented by a study investigator. Each modality presented the same study, "Sleep Drives Metabolite Clearance from the Adult Brain" (L. Xie, H. Kang, Q. Chen, Y. Liao, et al., Science 342:373–377, 2013, https://doi.org/10.1126/science.1241224). Knowledge about the study's scientific content was assessed before and after the randomly assigned learning modality using multiple-choice questions. Participants included a sample of college psychology students and a sample of community-dwelling older adults. Cognitive tests were used to assess individual differences in working memory, processing speed, science literacy, and semantic knowledge. Surveys were used to assess trust in science and scientists, attitudes toward science, and attitudes toward cognitive tasks. Results indicated that both younger and older adults can learn basic biomedical science from a primary source. Knowledge gains were observed in all three learning modalities with no evidence of age group differences. Notably, the largest learning gains for undergraduates and older adults were observed in the primary scientific article condition, followed by the TEDTalk, and the annotated paper. Baseline knowledge about the science study topic and adoption of "scientific attitudes" (e.g., open-mindedness) predicted learning across age groups and learning modalities. These findings suggest that science educators, communicators, and outreach professionals should consider methods of promoting science literacy in the general public through direct access to primary scientific sources.

KEYWORDS attitudes towards science, online learning, primary scientific literature, science literacy

INTRODUCTION

Science literacy broadly refers to "familiarity with the enterprise and practice of science" (1). Health literacy, referring to the "capacities of people to meet the complex demands of health in a modern society" is closely related to science literacy (2). It is assumed that greater science and health literacy could help improve informed decision-making at the individual and collective levels; however, there is little understanding on exactly how science literacy would help people be informed about science and their health or what kinds of skills science literacy would have to include to do so (3).

During the 2019 coronavirus disease (COVID-19) pandemic, it has become especially critical to understand how the general public can increase their science and health literacy through learning about biomedical research in a remote, online environment. Challenges to providing biomedical information are not trivial and include (i) distrust in media sources (4) and health experts (5) and (ii) misinformation spread on social media and other outlets (6). One sector of the general public, older adults, would benefit from effective, online learning modalities, especially those used to communicate biomedical science, as this sector is at greater risk for most chronic and progressive diseases (7–10). Another sector of the general public engaging in

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online learning are college students, given the steady rise in the proportion of college courses taught online (11) and the number of higher-learning institutions that have been forced to move to online during the COVID-19 pandemic (12–14). It is critical for the scientific community to determine best practices for sharing biomedical information online with both of these groups as a way to strengthen science and health literacy among the general public.

There is no shortage of science-focused videos, popular news articles, and websites among online social networks in our digital age. In the United States, 70% of the general public uses the Internet to find information about specific scientific issues (15). Tools that allow for more direct research dissemination will enhance the public's ability to critically assess the validity of media reports on, and claims about, scientific research. One such tool is annotated primary scientific literature, which is designed to help readers interpret complex science by overlaying additional information onto primary scientific literature (16). Preserving the original text of the research, as well as the context, is what makes annotated primary scientific literature unique from other genres that modify or rewrite the original text. Science in the Classroom (SitC; www.scienceintheclassroom.org) is the premier example of annotated primary scientific literature that, while primarily designed for classroom pedagogical use with undergraduate students, may also have potential for use with the general public. SitC annotations have been designed to be at the reading comprehension level of a first-year undergraduate student, and ongoing evaluation efforts have provided evidence that this goal is being met (17).

Online videos are also a tool for science communication, and TEDTalks represent a specialized genre of science communication via online videos. TEDTalks are designed to reach two distinct audiences: (i) experts and professionals on the topic and (ii) nonexperts who are simply interested in the topic (18). While hundreds of science-based TEDTalks are available, a recent study found that TED presenters were predominantly male and nonacademics (19). Critics have also noted the entertainment-heavy nature of TEDTalks, questioning whether their premise is science or a sales pitch (20). Little is known as to whether or not TEDTalks are able to teach new scientific information to the general public.

This study aimed to examine the effectiveness of existing online interventions targeted at advancing the general public's knowledge about biomedical science research. We selected sleep as our biomedical science topic for two reasons. First, we consider sleep to be somewhat of a "neutral" scientific topic, safe from the polarized and political lenses applied to scientific topics such as climate change and evolution (21). Second, sleep is critical for health across the life span and is a lifestyle habit that could be easily adapted should the participants choose to do so.

We selected the article "Sleep Drives Metabolite Clearance from the Adult Brain" as the scientific study at the center of our interventions (22). This scientific paper was the 2014 recipient of the American Association for the Advancement of Science Newcomb Cleveland Prize, awarded to the authors of an outstanding paper published in *Science*. This scientific paper truly represents a novel scientific study that is of interest across scientific disciplines and the general public.

Using content from Xie et al. (22), we investigated whether nonexpert audiences, specifically, college psychology students and older adults, can learn about basic biomedical science from primary sources and what type of primary source yields the greatest benefit. We also determined whether the efficacy of different online learning modalities depends on learner characteristics. We collected data on participants' semantic knowledge, fluid cognitive abilities, and attitudes toward science and learning and examined the predictive values of these measures. Data collection for each of these interventions will help to expand our knowledge base on whether specific forms of online learning interventions can enhance the general public's literacy on important biomedical topics and/or encourage their motivation to improve health behaviors.

We hypothesized that if optimal learning from primary sources requires a narrative format, primary scientific literature (PDF) and the TEDTalk conditions will yield the most benefit (hypothesis 1 [H1]). With the annotated article, participants were likely to move around the article in a nonlinear fashion using the annotation tools and, if they use the provided external links, they would leave the article, causing a break in the narrative format of the article. If optimal learning requires intrinsic interest and/or self-directed learning, the annotated article would yield the most benefit (H2). Annotations, and the option to engage with them or not, allowed for participants to follow their intrinsic interests. As we worked with the two different groups at two different age levels, we predicted that younger and older adults may differ in their ability to learn from primary sources (H3). Finally, as we were interested in individual difference measures, such as general cognitive abilities and attitudes toward science and learning that have been previously associated with learning abilities and outcomes, these factors could predict comprehension gains in the present study (H4).

METHODS

Participants

Participants were recruited from the University of Central Florida (UCF) to join a study investigating learning about scientific topics. UCF undergraduates from age 18 to 35 years old were recruited through the UCF Psychology Department participant pool (via SONA) and received course credit for completing the study. Our final sample included 85 undergraduates (Table 1). Participants of ages 60 to 90 years old were recruited through the UCF Learning and Longevity Research Network participant registry and received $30 for completing the study. Our final sample included 89 older adults (Table 1). Note that compensation (credit or money) was provided for completing the study, but compensation rates were not performance based (i.e., flat-rate compensation; participants could not earn more credit or money for better performance). Thus, while the two compensation types may have been differentially motivating, it

TABLE 1
Group characteristics of study participants

Age group and condition	*n*	Mean age	Gender (% female)
Older adults			
Original article	30	73.78	76.67%
Annotated article	30	70.70	73.33%
Video	29	72.96	71.43%
Younger adults			
Original article	30	18.83	53.33%
Annotated article	27	18.67	62.97%
Video	28	19.29	60.71%

was unlikely that this would yield differences in levels of effort or performance for younger versus older adults. The study took place in private lab rooms and took approximately 2 h.

Ethics statement

The UCF Institutional Review Board approved the study and informed consent was obtained from all participants prior to beginning study procedures.

Procedure

Figure 1 provides an overview of the study timeline and procedures. Prior to arrival, participants were assigned into one of the learning tool conditions: original article (PDF), annotated article, or video summary group. Group assignments counterbalanced and were not revealed to participants until they began the learning intervention phase of the study. Participants then completed a portion of the individual difference measures assessing cognition and attitudes (step 1). The remaining measures were completed at the end of the experiment to reduce possible cognitive fatigue effects on learning and knowledge retention in the main task. Individual difference measures selected for completion after the main task were those measuring characteristics that were least likely to be affected by the cognitive demand or science content of the main task (semantic knowledge, need for cognition). Participants then reviewed a research news brief that described a biomedical science study on some of the brain health benefits of sleep (step 2). The news brief was followed by a knowledge assessment, which measured knowledge for scientific content from the study using multiple-choice questions (step 3; see Appendix S1 in the supplemental material). Participants were not told that the knowledge assessment would be repeated. During the intervention phase (step 4), participants learned more about the study through their assigned learning modality and then completed a second assessment to measure change in study-related knowledge (step 5; see Appendix S1). Each of the learning modalities provided the information necessary to correctly answer each of the knowledge questions. Additional cognitive and survey measures (step 6) were then completed and participants received their compensation.

Cognitive measures

(i) Working memory. Working memory was assessed using a computerized 2-back task. In each trial, participants were shown one single-digit number on each sequentially presented trial screen and were asked to identify when the digit on the screen matched the digit they saw two trials back by pressing the space bar on the keyboard. The task included two blocks of 20 trials presented with an interstimulus interval of 2,000 ms.

(ii) Processing speed. Processing speed was measured with a computerized stimulus response task. On each trial, participants were asked to fixate on a cross at the center of the screen and press the space bar on the keyboard as quickly as possible when they saw a circle appear at the center location. The task included two blocks of 20 trials presented with a jittered interstimulus interval of 5,000 to 9,000 ms (mean, 7,000 ms).

(iii) Science literacy. We used the Test of Scientific Literacy Skills (TOSLS) (23) to specifically measure participant's baseline skill level of evaluating the validity of sources (TOSLS questions 10, 12, 17, 22, and 26). This group of questions was designed to measure whether users were able to distinguish between types of sources and identify bias, authority, and reliability. We were unable to administer the entire TOSLS, due to both lack of time and measures from the TOSLS that were not relevant to this study. The TOSLS was validated previously, and acceptable levels of reliability were found (the internal reliability of the TOSLS was 0.731and 0.748 on the pretest and posttest, respectively, falling within the acceptable range of reliability; internal consistency estimates above 0.70 are considered acceptable, and values above 0.8 are considered to reflect good test reliability [24]).

(iv) Semantic knowledge. We utilized the Shipley vocabulary test (25), a 40-question multiple-choice synonyms test. Vocabulary words were presented with four synonym choice options, with test words becoming increasingly more difficult (less commonly used words).

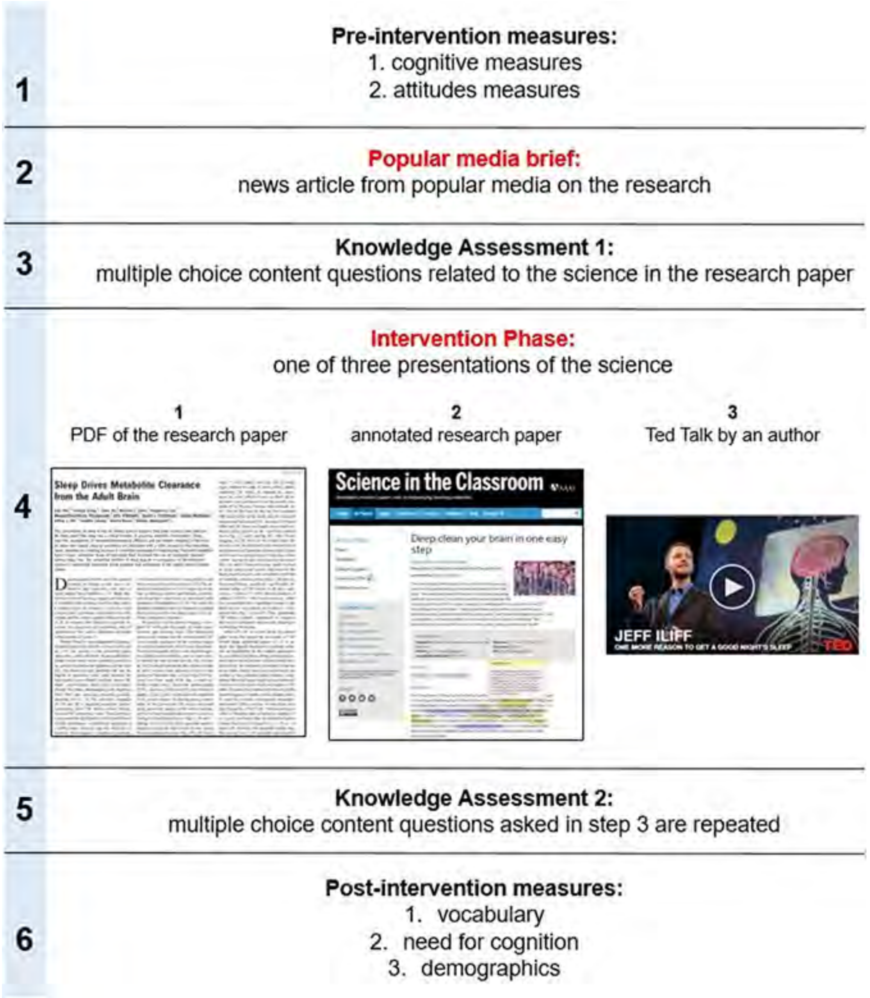

FIG 1. An overview of the study protocol.

Attitude measures

(i) Trust in science and scientists. The Trust in Science and Scientist Inventory (TSSI) (26) was administered to determine the preintervention baseline score of trust in science and scientists on a general level. This inventory has been validated for use as a means of assessing the impact of interventions intended to increase confidence and understanding of science and scientists and the subsequent influence on their trust in science. We included the full 21-question inventory. The TSSI was validated previously, and acceptable levels of reliability were found (internal reliability of 0.84).

(ii) Attitudes toward science. The Test of Science Related Attitudes (TORSA) (27, 28) was used to measure attitudes toward science in different contexts. TORSA includes seven different attitude subscales, of which we adapted three: adoption of scientific attitudes (questions 4, 18, 25, 39, 53, and 67), leisure interest in science (questions 13, 20, 27, 55, 62, and 69), and social implications of science (questions 1, 15, 22, 29, 43, and 57). Each separate attitude scale was scored independently. The TORSA was validated previously, and acceptable levels of reliability were found (0.78 [mean of scales]; attitude toward scientific inquiry, 0.75).

(iii) Attitudes toward cognitive tasks. The Need for Cognition (29) measure was used to assess participant's attitudes toward "effortful cognitive endeavors." This 18-item questionnaire indexes engagement and enjoyment of thinking, complex problem solving, and intellectual tasks.

Research news brief

A Facebook search was used to find the news brief written on the results of this research study. Facebook was considered a likely medium for the study population to come across science news. We selected a media source (http://www.care2.com) that was not well-known to reduce potential influences of prejudice against more well-known news sources (e.g., partisan reputations).

Primary source science learning modalities

(i) Primary scientific article. The article "Sleep Drives Metabolite Clearance from the Adult Brain" (22) was intervention

1. The first two pages of the PDF of the scientific article, as it appeared in *Science*, was shown digitally to participants using a desktop computer. Participants were given 20 min to read and explore the PDF on their own and had free control over scrolling and zooming in on the text.

(ii) Annotated article. The annotated version of Xie et al. (22) was presented to participants using the Science in the Classroom website. A special version of this annotated article was prepared for this study and included the same text and figure as the PDF version. Participants were given 20 min to read and explore the annotated article on their own and had free control over using the annotation tools.

(iii) Video summary. The TEDTalk presented by one of the article's authors, Jeff Iliff, was used as a video intervention. Participants were asked to watch the video in full (11 min 41 s; English closed captions were on) and were not able to rewatch sections of the video. We chose this implementation method as a way to create a naturalistic way that people would engage with a TEDTalk. Because people watch TEDTalks for enjoyment and for personal interests, they do not tend to review them many times as if they were studying for an exam or trying to understand difficult material.

We ensured that the content that was presented in all three modalities included all of the content that was in the comprehension assessment. In other words, for each of the three modalities, the answers to the content questions were available. The original *Science* article is only 3 pages long, yet we shortened this to 2 pages, which allowed readers to focus on the narrative content. The heavily technical Methods section, figure captions, and statistical analysis text that were removed were also not included in the TEDTalk. This also ensured that participants had the same amount of content they were asked to read in a comparable time requirement.

Assessments of scientific study-related knowledge (pre- to postintervention test performance change)

Learning of scientific content was assessed using a 17-question multiple-choice test (Appendix S1). Each question reflected content present in each of the three learning tools. Participants responded to these questions on the computer in a self-paced survey. Pre- and postintervention assessments had identical questions; however, participants were not informed that their knowledge would be tested after the learning intervention. Group means are presented with their standard errors (SEMs) and partial η_p^2 values are included as measures of effect size.

RESULTS

Optimal learning from primary sources

For the undergraduate students, analysis of variance (ANOVA) results for preintervention knowledge assessed in the multiple-choice test confirmed there were no baseline differences in knowledge among the learning modality groups [$F(2,82) < 1.00$, $P = 0.44$, $n_p^2 = 0.02$]. Our primary analysis examined learning modality effects on change in scientific study-related knowledge (pre- to postintervention test performance change [multiple-choice test]). Results revealed a significant effect for the intercept [$F(1,82) = 337.93$, $P < 0.001$, $n_p^2 = 0.81$]. This finding indicated significant learning among undergraduates across learning modality groups. We also observed a main effect of learning modality group, indicating different levels of knowledge gains by learning tool [$F(2,82) = 3.62$, $P = 0.03$, $n_p^2 = 0.08$]. Examination of means indicated the largest performance gains were in the primary article condition (mean = 4.27, SEM = 0.35; ~25.1% increase), followed by the video summary condition (mean = 3.79, SEM = 0.35; ~22.3% increase), then the annotated article condition (mean = 2.96, SEM = 0.35; ~17.4% increase) (Fig. 2). Tukey's honestly significant difference (HSD) *post hoc* pairwise comparisons indicated greater performance gains in the primary article condition relative to the annotated article condition ($P = 0.02$), but there were no other significant pairwise differences. These findings indicated that, while each of the learning tools was effective in enhancing scientific knowledge among undergraduates, the annotated article yielded slightly lower knowledge gains than the video summary (TEDTalk) and significantly lower gains than reading the original, primary research article.

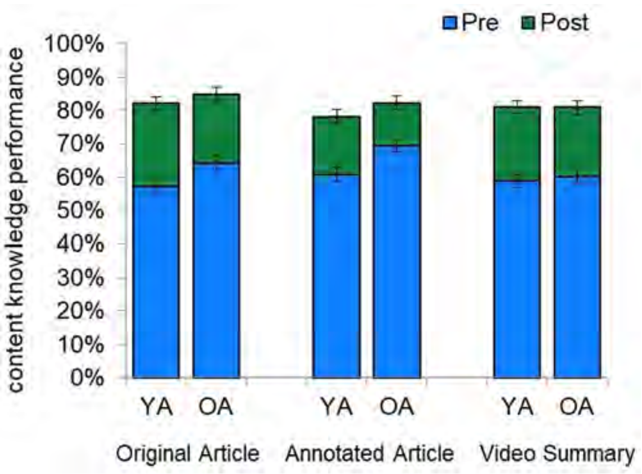

FIG 2. Effects of the three different learning modalities on participants' content knowledge performance.

For the older adults, ANOVA results for baseline knowledge about the scientific content assessed in the multiple-choice test revealed a small difference by condition [$F(2,86) < 3.27$, $P = 0.04$, $n_p^2 = 0.07$]. Inspection of means indicated that preintervention performance was highest in the annotated article group (mean = 11.80, SEM = 0.43; 69.4% correct), followed by the primary article group (mean = 0.93, SEM = 0.43; ~64.3% correct), and then the video summary group (mean = 10.24, SEM = 0.44; ~60.2% correct). Tukey's HSD *post hoc* pairwise comparisons indicated that older adults in the annotated article group had slightly higher baseline performance on the knowledge test than older adults in the video group ($P = 0.03$).

Because we saw preintervention differences among older adults by learning modality group, baseline knowledge test performance was included as a covariate in the analysis of change in knowledge test performance. ANCOVA results revealed a main effect of preintervention knowledge performance [$F(1,85) = 55.33$, $P < 0.001$, $n_p^2 = 0.39$], indicating that older adults with greater baseline knowledge had larger gains in their test performance with exposure to the learning tools. Results of the ANCOVA for knowledge change also revealed a significant effect for the intercept [$F(1,85) = 130.23$, $P < 0.001$, $n_p^2 = 0.61$]. This result confirmed improvements in knowledge test performance among older adults across groups. A marginal effect of learning modality group was observed [$F(2,85) = 2.72$, $P = 0.07$, $n_p^2 = 0.06$], suggesting subtle differences in knowledge gains on the multiple-choice test from pre- to postintervention by intervention modality. Consistent with results from the undergraduates, mean level performance gains in older adults were highest in the original article condition (mean = 3.47, SEM = 0.26; ∼20.4% increase), followed by the video summary condition (mean = 3.14, SEM = 0.27; ∼18.4% increase), and then the annotated article condition (mean = 2.59, SEM = 0.27; ∼15.2% increase) (Fig. 2). Thus, similar to findings with younger adults, older adults exhibited postintervention gains in scientific knowledge across learning modalities and somewhat-graded gains by learning modality. Notably, these consistent findings, including mean-level differences in knowledge gain by intervention condition, were observed while controlling for individual differences in preintervention performance.

Does learning from primary sources differ for younger and older adults?

We investigated whether younger and older adults differed in (i) learning gains overall (multiple-choice test performance change from pre- to postintervention) or (ii) if intervention modality interacted with age to impact learning gains. ANOVA results for baseline knowledge about the scientific content assessed in the multiple-choice test revealed no difference between the learning modality groups [$F(2,82) < 1.00$, $P = 0.44$, $n_p^2 = 0.02$].

ANOVA results for baseline content assessment performance revealed a main effect of age [$F(1,168) = 9.25$, $P = 0.003$, $n_p^2 = 0.05$], such that older adults had higher preintervention performance on the content assessment test (mean = 10.99, SEM = 0.23; ∼64.6% correct) than did younger adults (mean = 10.01, SEM = 0.23; ∼58.9% correct). We observed no interactions of age group and condition on preintervention performance [$F(2,168) = 1.34$, $P = 0.27$, $n_p^2 = 0.02$].

Analysis of covariance results for assessment performance change from pre- to postintervention revealed a main effect of preintervention performance [$F(1,167) = 91.40$, $P < 0.001$, $n_p^2 = 0.35$]. A *post hoc* Pearson correlation indicated that higher baseline performance was negatively correlated with performance change [$r(174) = -0.63$, $P < 0.001$]. Even with the inclusion of preintervention performance as a covariate, however, we found a significant effect for the intercept [$F(1,167) = 231.66$, $P < 0.001$, $n_p^2 = 0.58$], indicating reliable improvements from baseline across conditions. Consistent with the prior experiments' results, the cross-study analysis yielded a main effect of condition, indicating different levels of knowledge gains by learning tool [$F(1,167) = 5.52$, $P = 0.005$, $n_p^2 = 0.06$]. Examination of means indicated greater performance gains in the original article (mean = 3.78, SEM = 0.19; ∼22.2% increase) and video summary conditions (mean = 3.45, SEM = 0.20; ∼20.3% increase), relative to the annotated article condition (mean = 2.87, SEM = 0.20; ∼16.8% increase). Notably, we found no main effects of age group or an interaction of age group and condition (for both, $P > 0.68$), indicating similar intervention efficacy for young adults and older adults across and within learning tool intervention groups.

Thus, the assessment of age differences showed that older adults had greater knowledge at baseline (higher preintervention multiple-choice test performance) but exhibited the same pattern of gains as younger adults across and within intervention groups.

Role of cognitive abilities and attitudes toward science and learning influence learning biomedical science from a primary source

To examine individual differences in performance by cognitive ability and attitudes toward science and learning, we used a best-subsets regression. This approach employs the branch and bound algorithm (30) to exhaustively identify the best combination of predictors out of all possible subsets. This analysis was performed in R version 4.0.2 (31) (see Appendix S2 for details). In brief, the best-subsets method was applied to determine which combination of cognitive and attitude measures was the best predictor of (i) baseline scientific knowledge (i.e., baseline multiple-choice test performance), and (ii) improvements in scientific knowledge from pre- to postintervention. As described above, cognitive predictor measures included working memory, processing speed, science literacy, and semantic knowledge. Attitude predictor measures included trust in science and scientists, attitudes toward science, and attitudes toward cognitive tasks. Additionally, the analysis for predictors of improvements in scientific knowledge included baseline knowledge (preintervention multiple-choice test performance) as a cognitive predictor variable.

In predicting baseline scientific knowledge assessed on the multiple-choice test, results indicated that a combination of two measures provided the best prediction of performance: semantic knowledge ($b = 0.16$) and science literacy ($b = 0.43$; mean square error [MSE] = 3.75, Bayesian Information Criterion [BIC] = -28.74, Mallows' C_p-statistic [C_p] = -1.75, adjusted $R^2 = 0.22$). In predicting improvements in scientific knowledge from pre- to postintervention, the results revealed that the best subset of predictors was baseline scientific knowledge ($b = -0.55$) and adoption of scientific attitudes (a subscale of the attitudes towards science measure) ($b = 0.11$); (MSE = 62.28, BIC = -66.90, $C_p = 0.76$, adjusted $R^2 = 0.38$).

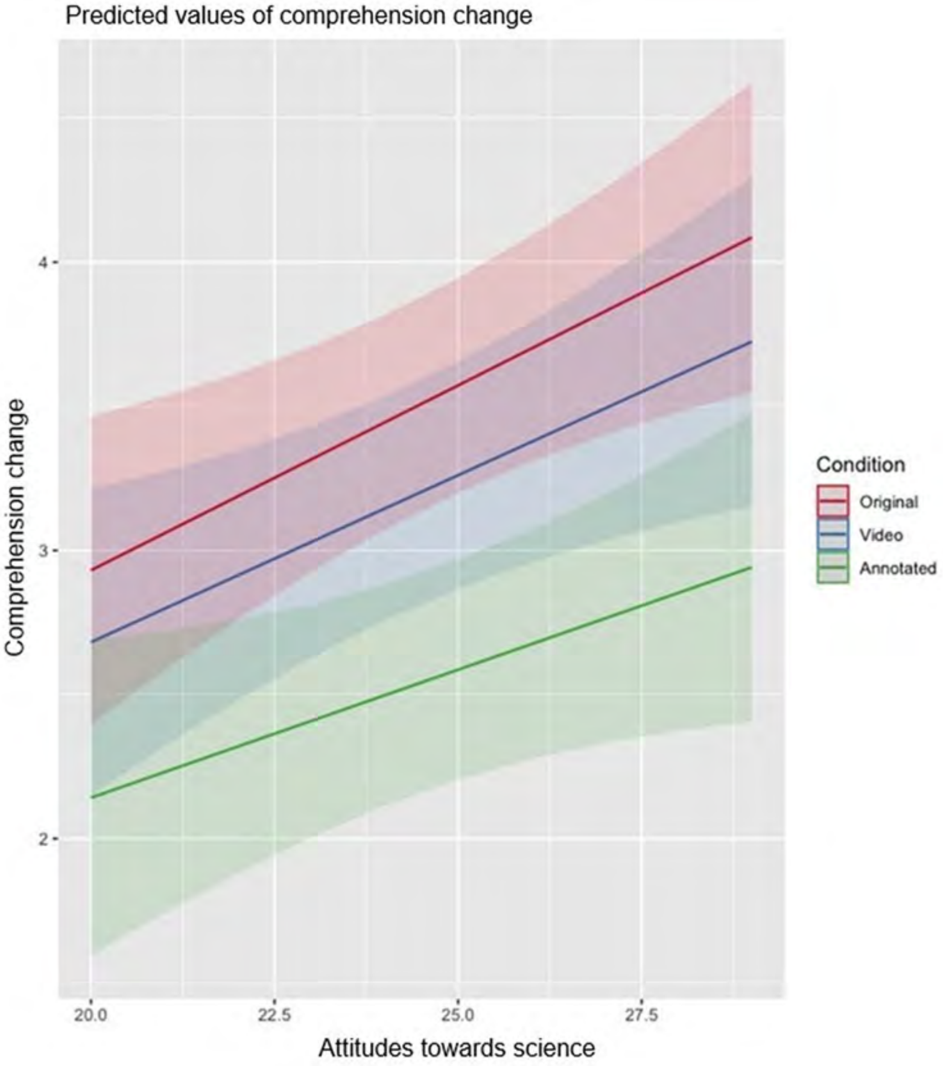

FIG 3. Assessment performance change predicted by adoption of science attitude. The *x* axis shows the sum score of participants' attitudes of science. The *y* axis shows the change in score (improvement) for participants on the comprehension change assessment (MC test). The positive slope indicates a positive, and predictive, relationship between these two individual difference measures.

These results indicated that, for the baseline knowledge assessment, participants' ability to correctly answer questions about the scientific topic of the learning intervention was related to their general semantic knowledge and science literacy. In contrast, participants' ability to learn new scientific knowledge about that same topic was predicted by their baseline knowledge about the topic itself, and critically, their adoption of "scientific attitudes," e.g., curiosity ("I am curious about the world in which we live"), open-mindedness ("I enjoy reading about things that disagree with my previous ideas"), and willingness to revise opinions ("I am unwilling to change my ideas when evidence shows that the ideas are poor"). As shown in Fig. 3, adoption of scientific attitudes predicted greater gains in performance on the multiple-choice test in each of the learning modality groups.

DISCUSSION

In this study, we compared the efficacy of different learning modalities by which primary scientific content can be accessed by the general public. We showed that both younger and older adults can learn basic biomedical science from a primary source by using all three treatment modalities: primary source research article, annotated research article, and video summary (TEDTalk). Supporting hypothesis 1, we showed that among three online modalities, the largest learning gains for both age groups were found with narrative formats. Specifically, learning gains were greatest for the original primary source *Science* article (PDF), followed by the TEDTalk, and then the annotated primary source article. We observed no age-related differences in learning gains between younger and older adults. We also found that prior specific knowledge about the topic and attitudes toward science predicted this learning.

The general public can read primary scientific literature

Our most exciting finding was that primary research articles are not only for students and academics! This was surprising, as the annotated article and TEDTalk formats were generally considered more accessible and possibly even an "on ramp" to the scientific article itself, and we hypothesized greater learning gains with the annotated treatment group (hypothesis 2). These data may help to overturn underlying assumptions that the general public is unable to read primary scientific articles which are rarely, if ever, written for or intended to be read by a general audience. Our data suggest that not only can the general public read primary scientific articles, but also that they are able to gain health-related information, which will impact their science literacy. We anticipate these results to be welcome news to science educators, communicators, and outreach professionals.

Age is not a predictor in understanding science content from a primary source

Cognitive abilities change as people age. Older adults tend to have poorer measures of fluid intelligence but greater semantic knowledge (32). Age differences in learning from primary sources may be explained by accounting for individual differences in cognitive abilities; however, we did not find any overall relationship between age differences and performance, as predicted by hypothesis 3. In fact, the younger adults, across all treatment groups, showed the same patterns in content knowledge performance as the older adults. Again, we anticipate these results to be welcome news to science educators, communicators, and outreach professionals; according to our data, older adults are just as likely to learn from their efforts, and increase their science and health literacy, as younger adults are. Further, as we have learned during the COVID-19 pandemic, learning about newly emerging biomedical science from reliable sources can play a critical role in protecting populations at greater risk for negative health events, like older adults.

Science literacy and attitudes toward science predict understanding science from a primary source

Supporting hypothesis 4, we showed that, prior to the learning intervention (preintervention knowledge assessment) (Fig. 1), the ability to answer specific questions about the scientific content covered in the research article was associated with science literacy and general semantic knowledge. Critically, however, the ability to learn new scientific knowledge (postintervention knowledge assessment) (Fig. 1) depends on one's adoption of "scientific attitudes" that index traits like curiosity and open-mindedness, as well as willingness to revise opinions (28) (Fig. 3), along with preexisting knowledge about that science topic (i.e., preintervention knowledge). Our study population was self-selected to a point: all participants were connected to a network that advertised an opportunity to join a study investigating learning about scientific topics, and they all willingly agreed. Therefore, we may have a population who was already interested in science and likely had a positive attitude toward science. However, even with this self-selected group, greater adoption of scientific attitudes was a strong predictor of gains in knowledge in each of the primary source interventions. While our study was not broad enough to investigate this finding in greater detail, these results will be valuable to expanding our understanding of how people become scientifically literate and who is most likely to benefit from exposure to science communicated from primary sources.

Limitations

We could not just pick any piece of primary research for this study. One reason for selecting our particular primary research article was access to matched stimuli across three separate conditions (PDF, annotations, and TEDTalk led by an author). While every research article will not be as adaptable as this one was, we have found that interdisciplinary journals, which are not meant for specialists, are fairly reader-friendly for people outside of academia. We believe our results will be most generalizable to interdisciplinary primary research articles.

This research is a simplified version of how the general public can access online science and biomedical information and learn from it. We recognize that in the real world the general public is unlikely to seek out a scientific article, whether it is annotated or not. However, our results suggest that science educators, communicators, and outreach professionals do not need to shy away from primary sources when developing online content. We have shown that it is possible to provide the general public with the primary science instead of filtering the science through various online and social media outlets and risking having the message change or, worse, turn into misinformation. Instead, our results promote the use of primary sources with the general public.

SUPPLEMENTAL MATERIAL

Supplemental material is available online only.

SUPPLEMENTAL FILE 1, DOCX file, 0.04 MB.

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