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Perceptions and responses to COVID-19 through wastewater surveillance information and online search behavior: A randomized controlled trial

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A R T I C L E I N F O

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Risk communication
Wastewater-based epidemiology

A B S T R A C T

An influence of wastewater surveillance during infectious disease outbreak on public perception and behavior remains unclear. Here, we used a randomized controlled trial to analyze the influence of wastewater surveillance-based information on “understanding of,” “interest in,” “relief regarding,” “preventive behavioral intention against,” and “subsequent online search behavior related to” COVID-19. Valid responses were obtained from 1000 individuals in both control and intervention groups from Yahoo! JAPAN crowdsourcing users aged ≥18 years in Japan. This survey was conducted from August 4 to August 7, 2023, just before the common Japanese tradition of returning to hometowns. The questionnaire not only collected personal attributes but also gauged responses to COVID-19 information. This information highlighted the early detection capabilities and representativeness of wastewater surveillance compared with sentinel surveillance at medical institutions. At one-week post-survey, we obtained the survey participants’ online search history for key words such as “bullet train,” “highway,” “airplane,” and “wastewater.” Wastewater surveillance-based information did not notably elevate “understanding” or “specific intentions” regarding COVID-19, such as wearing masks and receiving vaccination. However, it significantly increased “interest in,” “relief concerning the infection status,” and “general preventive behavioral intentions.” Heightened “interest” and “general preventive intentions” did not depend on prior interest or behavior. However, those who previously engaged in preventive behavior or who were less interested in COVID-19 exhibited more “relief” after exposure to wastewater surveillance-based information. Furthermore, this information could slightly influence online searches, such as highways. In conclusion, information from wastewater surveillance effectively shapes individual perceptions of and responses to infections.

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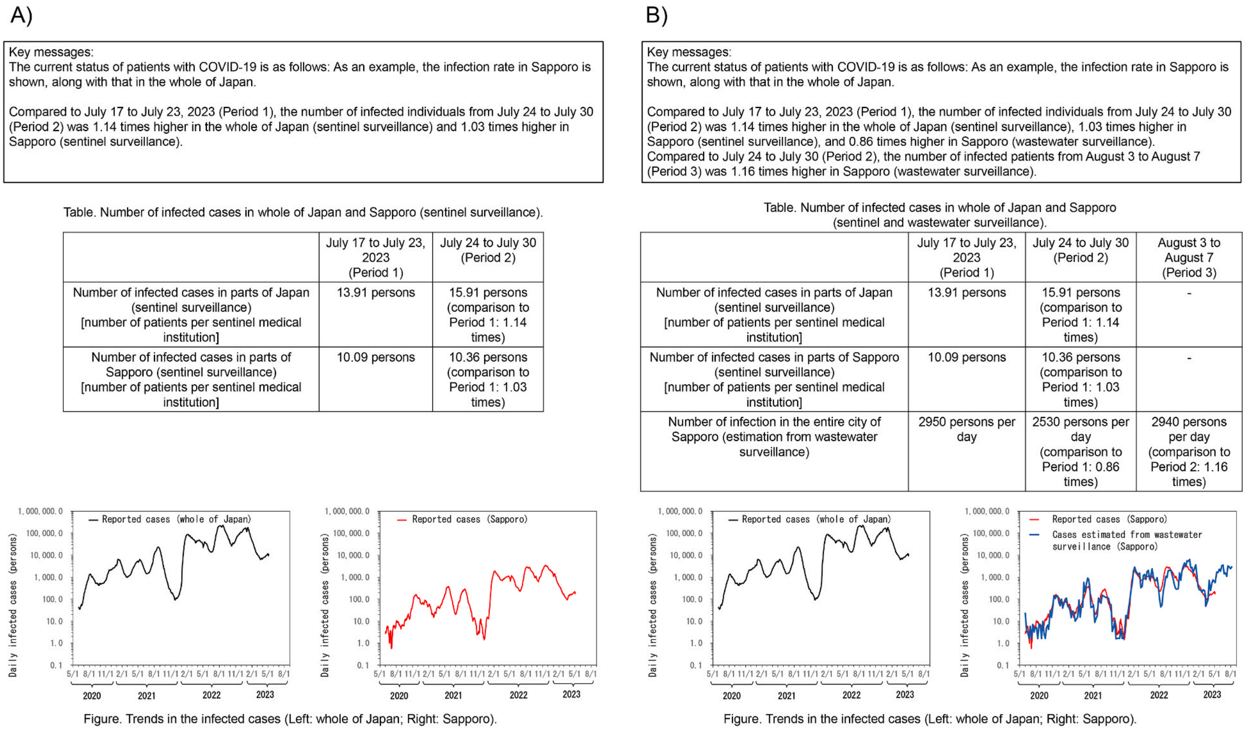
1. Introduction

During an infectious disease outbreak, it is vital to monitor infection status over time, including tracking the daily number of infected individuals. Infectious disease surveillance helps ensure adequate medical resources, such as hospital capacity [1]. Furthermore, sharing information about the infection status can prompt the public to adopt preventive behavior [2], which is useful in preventing the spread of infectious diseases [3,4]. Since the onset of the coronavirus disease 2019 (COVID-19) pandemic, data on daily infections have been widely disseminated in many countries [5]. However, as the severity of the COVID-19 pandemic has decreased, obtaining a comprehensive picture of the infection status has become challenging. Comprehensive or random sampling surveys can be costly, and some symptomatic individuals avoid seeking medical attention [6].

Measuring pathogenic microorganisms in the influent of wastewater treatment plants (referred to as wastewater surveillance) provides a representative view of infection in a particular area. Wastewater surveillance can be more economical and faster than clinical surveillance for understanding the prevalence of infectious diseases in a community and can lead to earlier detection [7,8]. Research has shown that concentration of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in wastewater foreshadows the number of clinically confirmed cases in the corresponding population, enabling earlier outbreak alerts [9–12]. Although surveillance of wastewater discharged from facilities has been used to encourage testing and preventive behavior against infection for residents of those facilities [13,14], information based on surveillance at wastewater treatment plants has also been used to understand trends in infection status, particularly by experts [6]. In Japan, since the reclassification (i.e., downgrading) of COVID-19's legal status on May 8, 2023, infections have been tracked using weekly reports from selected sentinel medical institutions. This change has led to delays in understanding real-time infection status. Consequently, wastewater surveillance, which provides quicker insights (approximately 1–2 weeks earlier than sentinel surveillance), has gained prominence [11].

Current wastewater surveillance data are available on dedicated websites, such as those provided by the U.S. Centers for Disease Control and Prevention [15] and the Netherlands' Coronavirus Dashboard [16]. In Japan, some local governments also share wastewater surveillance data [17,18]. Few studies have examined public attitudes toward wastewater surveillance, with most respondents appreciating its utility [19–21]. Providing wastewater surveillance data could be useful in preventing the spread of infection if it does in fact change individuals' perceptions of their infection status and encourage infection prevention behaviors. However, the impact of this form of surveillance on the public interest in COVID-19 and its preventive behavior remain unclear.

Therefore, this study aimed to investigate how presenting wastewater surveillance data that reflected infection status influenced people's perceptions and behavior related to COVID-19. We compared the reactions to information from sentinel surveillance alone with those from a combination of wastewater and sentinel clinical surveillance data. Specifically, we conducted a questionnaire survey to gauge participants' "understanding of," "interest in," "relief regarding," and "intent to adopt preventive behavior" after presenting the wastewater surveillance data. These outcomes were selected because preventive behavior is related to understanding, interest, and



A)

Key messages:
The current status of patients with COVID-19 is as follows: As an example, the infection rate in Sapporo is shown, along with that in the whole of Japan.

Compared to July 17 to July 23, 2023 (Period 1), the number of infected individuals from July 24 to July 30 (Period 2) was 1.14 times higher in the whole of Japan (sentinel surveillance) and 1.03 times higher in Sapporo (sentinel surveillance).

Table. Number of infected cases in whole of Japan and Sapporo (sentinel surveillance).

	July 17 to July 23, 2023 (Period 1)	July 24 to July 30 (Period 2)
Number of infected cases in parts of Japan (sentinel surveillance) [number of patients per sentinel medical institution]	13.91 persons	15.91 persons (comparison to Period 1: 1.14 times)
Number of infected cases in parts of Sapporo (sentinel surveillance) [number of patients per sentinel medical institution]	10.09 persons	10.36 persons (comparison to Period 1: 1.03 times)

Figure. Trends in the infected cases (Left: whole of Japan; Right: Sapporo).

B)

Key messages:
The current status of patients with COVID-19 is as follows: As an example, the infection rate in Sapporo is shown, along with that in the whole of Japan.

Compared to July 17 to July 23, 2023 (Period 1), the number of infected individuals from July 24 to July 30 (Period 2) was 1.14 times higher in the whole of Japan (sentinel surveillance), 1.03 times higher in Sapporo (sentinel surveillance), and 0.86 times higher in Sapporo (wastewater surveillance).
Compared to July 24 to July 30 (Period 2), the number of infected patients from August 3 to August 7 (Period 3) was 1.16 times higher in Sapporo (wastewater surveillance).

Table. Number of infected cases in whole of Japan and Sapporo (sentinel and wastewater surveillance).

	July 17 to July 23, 2023 (Period 1)	July 24 to July 30 (Period 2)	August 3 to August 7 (Period 3)
Number of infected cases in parts of Japan (sentinel surveillance) [number of patients per sentinel medical institution]	13.91 persons	15.91 persons (comparison to Period 1: 1.14 times)	-
Number of infected cases in parts of Sapporo (sentinel surveillance) [number of patients per sentinel medical institution]	10.09 persons	10.36 persons (comparison to Period 1: 1.03 times)	-
Number of infection in the entire city of Sapporo (estimation from wastewater surveillance)	2950 persons per day	2530 persons per day (comparison to Period 1: 0.86 times)	2940 persons per day (comparison to Period 2: 1.16 times)

Figure. Trends in the infected cases (Left: whole of Japan; Right: Sapporo).

Fig. 1. Information provided to participants. A) absence of wastewater surveillance information (control group); b) presence of wastewater surveillance information (intervention group).

anxiety [22]. Additionally, we analyzed the participants' online search behavior one-week post-survey, considering that people's stated intentions may not always match their actions. As actual behavior is expected to follow heightened intentions as thus measured [23], a follow-up survey not considering prevention behavior intentions is needed to assess whether or not the prevention behavior was implemented. We believe that their online search behavior could reflect the shifts promoted by wastewater data.

2. Methods

2.1. Ethics

This study was approved by the Ethics Committee of the Center for Infectious Disease Education and Research at Osaka University (approval number 2023CRER0612). All participants provided informed consent.

2.2. Surveys

This study was designed as a randomized controlled trial. Participants were randomly selected and divided into control (n = 10,000) and intervention (n = 10,000) groups out of approximately 50,000 active users of Yahoo! JAPAN's crowdsourcing service (Yahoo! JAPAN crowdsourcing) as of July 2023. These users were part of a larger pool of approximately one million registered users, all of whom were aged ≥15 years in Japan. An online survey was targeted for those aged ≥18 years and conducted for both groups between August 4 and August 7, 2023 until 1000 valid responses were collected from each group.

The primary goal of this study was to understand the influence of providing information on wastewater surveillance, which reflected the infection status on individuals' perceptions of and responses to COVID-19. The sample size was determined in consultation with Yahoo! JAPAN based on survey feasibility and a lack of prior knowledge regarding the potential impact of such information. With a population size of 125,000,000 in Japan, a sample size of approximately 400 is needed to achieve a 5 % margin of error with a 95 % confidence interval [24]. The sample size of this study surpassed that benchmark.

The questionnaires and information presented in the survey were written in Japanese. For both the control and intervention groups, data from more than 40 % of the targeted participants were collected on August 4, and by August 5, the rate had exceeded 80 % (Fig. S1). Our survey coincided with the custom period in Japan when many people returned to their hometowns in mid-August. Many people took vacation days between August 11 (a national holiday) and 16. The participants assessed the infection status information using the URL provided (Fig. 1). Those who answered "I did not read the content carefully" were excluded (27 in the control group and 36 in the intervention group). Participants who provided valid responses received a reward equivalent to 100 Japanese Yen.

2.2.1. Interest in and preventive behavior against COVID-19 before providing information

The questionnaire comprised four major sections. Two authors [MM (specializing in risk science and environmental engineering) and SN (focusing on epidemiology and public health)] with expertise in risk perception and preventive behavior regarding COVID-19 [25,26] were consulted to frame the questionnaire survey in the context of the COVID-19 pandemic. Furthermore, to ensure content validity, these two authors developed the questionnaire items in consultation with each other.

In the first section, prior to introducing any information on the infection status (covered in the second section), the participants rated their interest in COVID-19, changes in case numbers, their overall preventive behavior, mask usage, and attitudes toward vaccination using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). These evaluations were later labeled as "interest in COVID-19 (pre)," "interest in infection status (pre)," "overall preventive behavior (pre)," "mask-wearing (pre)," and "awareness of the importance of COVID-19 vaccine (pre)."

2.2.2. Information provided to participants

Participants were then given different sets of information in the second section, depending on whether they were in the control or intervention group (Fig. 1). The control group received the latest data on the numbers of reported cases from all of Japan and Sapporo [27], including specific details from the two periods in July 2023 [July 17 to July 23, 2023 (Period 1), and July 24 to July 30 (Period 2)], along with a comparison of these periods. This information was shown both narratively and tabularly. Moreover, the number of daily reported cases from June 1, 2020 to May 7, 2023 in both Japan and Sapporo was represented by a figure.

The intervention group received information on wastewater surveillance in Sapporo, in addition to the number of cases described above. The wastewater surveillance estimated the number of cases in Sapporo for five days after sample collection based only on the SARS-CoV-2 concentration in wastewater [11]. In addition to the data for Periods 1 and 2, the estimated figures from August 3 to August 7 (Period 3) and its ratio compared with Period 2 were also provided tabularly with a key message. The wastewater surveillance data estimated the total number of infected individuals in Sapporo from June 2020 to August 7, 2023, which was represented by a figure. This estimate was compared to the total confirmed cases from a notifiable clinical surveillance conducted throughout Japan and Sapporo until the downgrading of the legal status of COVID-19 (May 8, 2023), showing good agreement between the estimated and clinically confirmed cases in Sapporo.

Sapporo was chosen because of its capability to present estimates of the number of infected individuals [11] and because of their local government's weekly updates on COVID-19 information based on wastewater surveillance on its website [17].

As the information was presented to non-specialists, important key messages were shown first, particularly regarding how the ratio information indicated the changes in infection status. To ensure the reliability of the information, supplementary explanations were provided as a table and figure.

2.2.3. "Understanding of," "interest in," "relief regarding," and "intentions for preventive behavior against" the COVID-19 infection status

In the third section, following the presentation of COVID-19 information in the second section and ensuring that the participant had read the content (which was confirmed with a "I read the content carefully" or "I did not read the content carefully"), respondents were prompted to indicate their "understanding of," "interest in," and "relief regarding" the COVID-19 infection status. They also provided their intentions for overall preventive behavior, mask-wearing, and vaccination as control measures using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). These evaluations were subsequently labeled as "understanding of infection status (post)," "interest in infection status (post)," "relief regarding infection status (post)," "intent to engage in overall preventive behavior (post)," "intent to wear masks (post)," and "intent to receive COVID-19 vaccine (post)."

2.2.4. Personal attributes

In the fourth section, the participants responded to questions about their gender, age, place of residence (at the prefecture level), and history of COVID-19. There were no missing data for any of the survey items.

2.2.5. Online search behavior

Next, we obtained population-based data on online search behavior from Yahoo! JAPAN. These data captured participants' Yahoo! JAPAN search engine usage within one week before and after the online survey for both the control and intervention groups. Specifically, we first obtained information regarding the top 100 and bottom 100 keywords with the most significant search differences between the two groups post-survey. Based on this information, we established the following five lists of search keywords (terms in the keyword lists are indicated by double quotation marks).

(1) "bullet train" [*jr Hokkaido* or *jr East Japan* or *jr Tokai* or *jr West Japan* or *jr Shikoku* or *jr Kyushu* or *Shinkansen* (bullet train)]
(2) "highway" [*kousokudouro* (highway)]
(3) "airplane" [*ana* or *jal* or *Zennihonkuuyu* (All Nippon Airways) or *Zennikkuu* (an abbreviation of All Nippon Airways) or *Koukuu* (an abbreviation of Japan Airlines) or *hikouki* (airplane) or *kuukou* (airport)]
(4) "COVID-19" [*korona* (corona) or *covid*]
(5) "wastewater" [*gesui* (wastewater)].

The Japanese keyword lists are presented in Table S1. Lists (1) and (3) represent bullet trains with their respective operators and airplane-related terms, including major Japanese airlines, respectively.

As mentioned earlier, due to Japanese customs, the period after the questionnaire survey ended on August 7, 2023, was when many people returned to their hometowns. Considering the decreased travel in Japan during 2020 and 2021 because of the COVID-19 pandemic [28], increased travel by mid-August 2023 was anticipated, after the downgrading of COVID-19's legal status. In Japan, bullet trains, highways, and airplanes are means of transportation commonly used by travelers returning to their hometowns. Therefore, we decided to use keyword lists (1) to (3). Keywords were extracted even when flanked by other characters [e.g., *koronauirusu* (i.e., coronavirus)] and were recognized irrespective of half-width or full-width characters, or case distinction.

Data regarding the search numbers within a week before and after the survey were obtained for both groups. If the search count was five or less, the exact number was withheld. Additionally, we acquired data on the ratio of the total Yahoo! JAPAN searchers in the week before and after the survey. The post-survey Yahoo! JAPAN user count was 1.0050 times greater than that in the pre-survey.

2.3. Statistical analysis

First, to confirm the reliability of the questionnaire items regarding intention and prevention behavior before the wastewater surveillance information was provided, we used the Spearman-Brown coefficient for "interest in COVID-19 (pre)" and "interest in infection status (pre)," and Cronbach's α for "overall preventive behavior (pre)," "mask-wearing (pre)," and "awareness of the importance of COVID-19 vaccine (pre)." Since both coefficients were sufficiently high at 0.879 and 0.718, respectively, the questionnaire items were judged reliable. In this study, however, the scores of the questionnaire items were treated separately in this later analysis.

Second, to ensure that the random assignment of the participants was done properly, we performed Z-pooled exact unconditional, chi-square, Fisher-Freeman-Halton, or Mann-Whitney's *U* tests to investigate differences in "interest in COVID-19 (pre)," "interest in infection status (pre)," "overall preventive behavior (pre)," "mask-wearing (pre)," "awareness of the importance of COVID-19 vaccine (pre)," gender, age, prefecture of residence [Hokkaido (prefecture where Sapporo is located) or other prefectures], and history of COVID-19 infection between the control and intervention groups.

Next, we calculated Spearman's correlation coefficients for the control and intervention groups among "understanding of infection status (post)," "interest in infection status (post)," "relief regarding infection status (post)," "intent to engage in overall preventive behavior (post)," "intent to wear masks (post)," and "intent to receive COVID-19 vaccine (post)." The distribution of "understanding of infection status (post)" for both groups was analyzed descriptively. We then used Mann-Whitney's *U* test to assess differences in "understanding of infection status (post)," "interest in infection status (post)," "relief regarding infection status (post)," "intent to engage in overall preventive behavior (post)," "intent to wear masks (post)," and "intent to receive COVID-19 vaccine (post)" between the control and intervention groups. Furthermore, to examine how participants' psychological factors had an additional effect of the intervention on the outcomes, we performed ordinal logistic regression analyses for "interest in infection status (post)," "relief regarding infection status (post)," and "intent to engage in overall preventive behavior (post)" that showed the significant differences in the Mann-Whitney's U test above. The intervention, "interest in COVID-19 (pre)," "overall preventive behavior (pre)," and their interaction terms with the intervention were used as explanatory variables. "Interest in COVID-19 (pre)" and "overall preventive behavior (pre)" were centered. The variance inflation factor was 1.00 for the intervention and 3.06–3.43 for the other variables, indicating that multicollinearity was sufficiently small.

Finally, we compared the proportion of searchers for each keyword list between the control and intervention groups in the week before and after responding to the questionnaire survey. For this purpose, we used a Z-pooled exact unconditional test. This test was chosen because its appropriateness in evaluating associations in two × two tables, especially when dealing with a low number of searchers [29]. Analyses were conducted using IBM SPSS 28 (IBM, Chicago, IL, USA) or R [30,31].

3. Results

3.1. Assessment of the random assignment of the participants based on the individual attributes and interest in and preventive behavior against COVID-19 before providing information

To validate whether the random assignment of the participants was done properly, Table 1 presents a simple tabulation of the survey results regarding the differences in the characteristics of participants in the control and intervention groups before the presentation of information on infection status. There were no significant differences ($P > 0.05$; φ = −0.010, Cramer's V = 0.010–0.061, r = −0.011–0.028) in individual attributes such as gender, age, prefecture of residence, history of COVID-19, or in interest in and preventive behavior regarding COVID-19 before the presentation of information.

3.2. Effect of wastewater surveillance information on "understanding of," "interest in," "relief regarding," and "intent to adopt preventive behavior"

There were no significant associations of "relief regarding infection status" with "interest in" and "intention for preventive

Table 1
Participants' characteristics. N: number of participants; SD: standard deviation.

		N (%) or *mean (SD)*		*φ*, Cramer's *V*, or *r*	*P*
		Control	Intervention		
Gender	Woman	276 (27.6 %)	269 (26.9 %)	0.033	0.571
	Man	717 (71.7 %)	719 (71.9 %)		
	Other	1 (0.1 %)	4 (0.4 %)		
	Don't answer	6 (0.6 %)	8 (0.8 %)		
Age	18–29	38 (3.8 %)	30 (3.0 %)	0.061	0.396
	30–39	116 (11.6 %)	100 (10.0 %)		
	40–49	265 (26.5 %)	294 (29.4 %)		
	50–59	331 (33.1 %)	348 (34.8 %)		
	60–69	167 (16.7 %)	166 (16.6 %)		
	70–79	73 (7.3 %)	53 (5.3 %)		
	80 and more	4 (0.4 %)	4 (0.4 %)		
	Don't answer	6 (0.6 %)	5 (0.5 %)		
Prefecture	Hokkaido	39 (3.9 %)	43 (4.3 %)	−0.010	0.671
	Other	961 (96.1 %)	957 (95.7 %)		
Covid history	Yes	193 (19.3 %)	189 (18.9 %)	0.010	0.901
	No	803 (80.3 %)	808 (80.8 %)		
	Don't answer	4 (0.4 %)	3 (0.3 %)		
Interest in and preventive behavior against COVID-19 before providing information[a]	Interest in COVID-19 (pre)	*3.51 (1.04)*	*3.52 (1.06)*	0.010	0.666
	Interest in infection status (pre)	*3.25 (1.15)*	*3.32 (1.15)*	0.028	0.209
	Overall preventive behavior (pre)	*3.80 (1.00)*	*3.82 (0.95)*	0.001	0.968
	Mask-wearing (pre)	*3.69 (1.32)*	*3.66 (1.34)*	−0.011	0.616
	Awareness of the importance of COVID-19 vaccine (pre)	*3.40 (1.24)*	*3.41 (1.19)*	−0.004	0.857

[a] Option ranges: 1–5.

behavior" in either the control or intervention groups after the information presentation (Table S2; $P > 0.05$; −0.060–0.044), except for the association between relief regarding infection status (post) and intent to receive COVID-19 vaccine (post) in the intervention group ($P < 0.05$; 0.111–0.139). By contrast, significant associations were observed between "interest in" and "intention for preventive behavior" ($P < 0.05$; 0.265–0.786). For example, the Spearman's correlation coefficient between interest in infection status (post) and intent to engage in overall preventive behavior (post) in the intervention group was 0.639 ($P < 0.001$).

"Understanding of infection status (post)" was 60.6 % for "agree (=4)" and 13.6 % for "strongly agree (=5)" in the control group, and 60.6 % and 11.7 %, respectively, in the intervention group. Table 2 shows the simple tabulation of the survey results regarding the differences in "understanding of," "interest in," "relief regarding," and "intention for preventive behavior regarding" COVID-19 between the two groups after information presentation. Interest in infection status (post), relief regarding infection status (post), and intent to engage in overall preventive behavior (post) in the intervention group were significantly higher than those in the control group ($P < 0.05$; $r = 0.045$–0.048). No significant differences were found in understanding of infection status (post), intent to wear masks (post), and intent to receive COVID-19 vaccine (post) ($P > 0.05$; $r = -0.027$–0.021).

Table 3 shows the associations of interest in COVID-19 (pre), overall preventive behavior (pre), intervention, and their interaction terms with interest in infection status (post), relief regarding infection status (post), and intent to engage in overall preventive behavior (post). All outcomes were significantly and positively associated with the intervention ($P < 0.05$; aOR [adjusted odds ratio] = 1.17–1.29). Interest in COVID-19 (pre) and overall preventive behavior (pre) were significantly and positively associated with interest in infection status (post) and intent to engage in overall preventive behavior (post) ($P < 0.05$; aOR = 1.85–4.02), whereas their interaction terms with intervention were not significantly associated with these two outcomes ($P > 0.05$; aOR = 0.83–1.17). In contrast, overall preventive behavior (pre) and the interaction term with intervention were significantly negatively and positively associated with relief regarding infection status (post), respectively ($P < 0.05$; aOR = 0.80 and 1.24). Interest in COVID-19 (pre) was not significantly associated with relief regarding infection status (post) ($P > 0.05$; aOR = 1.06), but its interaction term with intervention showed a significant negative association ($P < 0.05$; aOR = 1.24).

3.3. Effect of wastewater surveillance information on online search behavior

Table 4 presents a simple tabulation of the survey results regarding the proportion of participants who engaged in search behavior after the survey was administered. The proportion of participants who searched for "bullet train" was marginally higher in the intervention group than in the control group, although the difference was not significant ($P = 0.129$; $\varphi = 0034$). When substituting the number three for "highway" (i.e., 1/2 of the upper limit rounded to the nearest integer) in the control group, the intervention group had a significantly higher proportion of searchers ($P < 0.05$; $\varphi = 0048$). However, using the upper limit of five, the difference was not significant ($P = 0.146$; $\varphi = 0034$). The proportions of participants who searched for "airplane" and "COVID-19" were similar between the two groups ($P > 0.05$; $\varphi = -0.025$–0.004). The number of participants who searched for "wastewater" was ≤5 for each group.

Table S3 presents a simple tabulation of the survey results regarding the proportion of participants who searched for keyword lists during the week before the survey. There was no significant difference in the proportion of participants who searched for any of the keyword lists between the two groups ($P > 0.05$; $\varphi = -0.022$–0.000).

4. Discussion

Using a randomized controlled trial design, this study investigated whether the presentation of information on COVID-19 infection status based on wastewater surveillance increased "interest in," "relief regarding," and "intention for preventive behavior against" COVID-19. We also analyzed changes in online search behavior after the provision of the aforementioned information.

Table 2
Differences in "understanding of," "interest in," "relief regarding," and "intention for preventive behavior against" COVID-19 after providing information. All options ranged from 1 to 5. SD: standard deviation.

	mean (SD)		r	P
	Control	Intervention		
Understanding of infection status (post)	3.79 (0.79)	3.76 (0.77)	−0.027	0.225
Interest in infection status (post)	3.33 (1.05)	3.43 (1.02)	0.048	0.032
Relief regarding infection status (post)	2.58 (0.99)	2.67 (1.00)	0.045	0.043
Intent to engage in overall preventive behavior (post)	3.62 (1.04)	3.71 (1.03)	0.048	0.032
Intent to wear masks (post)	3.51 (1.24)	3.55 (1.25)	0.021	0.345
Intent to receive COVID-19 vaccine (post)	3.09 (1.29)	3.11 (1.28)	0.006	0.783

Table 3

Associations of intervention, interest (pre), overall preventive behavior (pre), and their interaction terms with interest (post), relief (post), and intent to engage in overall preventive behavior against COVID-19 (post). VIF: variance inflation factor; aOR: adjusted odds ratio; CI: confidence interval.

		aOR (95 % CI)		
	VIF	Interest in infection status (post)	Relief regarding infection status (post)	Intent to engage in overall preventive behavior (post)
Intervention	1.00	1.23 (1.05–1.45)	1.17 (1.00–1.38)	1.29 (1.08–1.53)
Interest in COVID-19 (pre)	3.40	2.91 (2.50–3.38)	1.06 (0.92–1.22)	2.03 (1.74–2.36)
Overall preventive behavior (pre)	3.16	1.85 (1.59–2.15)	0.85 (0.73–0.98)	4.02 (3.41–4.74)
Intervention * Interest in COVID-19 (pre)	3.29	0.94 (0.77–1.15)	0.80 (0.66–0.97)	0.83 (0.68–1.02)
Intervention * Overall preventive behavior (pre)	3.06	0.87 (0.70–1.08)	1.24 (1.01–1.53)	1.17 (0.94–1.46)

Table 4

Differences in proportions of keyword searches after providing information. N: number of participants.

	N (%)		φ	P
	Control	Intervention		
"Bullet train"	21 (2.1 %)	32 (3.2 %)	0.034	0.129
"Highway"	≤5 (≤0.5 %)	11 (1.1 %)	0.034[a] (0.048)[b]	0.146[a] (0.034)[b]
"Airplane"	47 (4.7 %)	37 (3.7 %)	−0.025	0.273
"COVID-19"	16 (1.6 %)	17 (1.7 %)	0.004	0.915
"Wastewater"	≤5 (0.5 %)	≤5 (0.5 %)	–	–

[a] "5" (i.e., the upper limit) was used for the number of control group.

[b] "3" (i.e., 1/2 of the upper limit rounded to the nearest integer) was used for the number of control group.

4.1. Assessment of the random assignment of the participants

The participants in this study did not differ in gender, age, place of residence, history of COVID-19 infection, and interest in and preventive behavior against COVID-19 prior to information presentation. Similarly, the proportion of participants who searched for each keyword list prior to the survey was consistent between the control and intervention groups. This confirmed that the randomization assignment of the participants was executed well based on the observed variables.

4.2. Effect of wastewater surveillance information on perceptions and responses to COVID-19

Next, the presentation of information on infection status based on wastewater surveillance was rated as understandable by more than 70 % of participants, and this information increased "interest in," "relief regarding," and "intention for overall preventive behavior against" COVID-19. This finding underscores the utility of such information. Furthermore, this information presentation may have caused a slight uptick in search behavior related to highways as a mode of transportation. However, the difference between the control and intervention groups was not clearly specified, because the number of participants who searched was below the upper limit in the control group. In addition, although not significant, there was a trend toward more searches related to bullet trains in the intervention group. Such spikes in search behavior may imply an increase in return travel during the mid-August vacation season.

Traffic volume on highways from August 9 to August 16, 2023 (approximately one week post-survey) was 1.07 times that in 2022 [32]. On August 10, 2023, potential nationwide cancellations of bullet trains owing to Typhoon No. 7, including JR Tokai bullet trains connecting major cities, were announced. Subsequently, there were cancellations and delays between August 15 and 17, 2023. The passenger count on the JR Tokai bullet train from August 10 to August 17 was 1.25 times that in 2022 [33]. Therefore, after the survey, it is likely that participants who planned to return or travel during the mid-August vacation season began searching for highway and bullet train-related terms. The wastewater surveillance data presentation might have nudged people toward pre-COVID-19 routine behavior, such as using highways or bullet trains for travel, along with a rise in "interest in," "relief regarding," or "intention for preventive behavior against" COVID-19.

4.3. Mechanisms for perceptions and responses to COVID-19 through wastewater surveillance information

It is challenging to interpret why wastewater surveillance-based information intensified "interest in," "relief regarding," and "intention toward overall COVID-19 preventive behavior," and why there was a spike in search behavior related to highways. One of the assumptions underlying the utility of presenting wastewater surveillance-based information is that people generally have a favorable perception of the wastewater surveillance approach [19–21].

This study also indicated that significant associations existed between "interest in" and "intention for overall preventive behavior" post-presentation. However, no significant associations were observed between "relief regarding" and either "interest in" or "intention for overall preventive behavior." Results from the ordinal logistic regression analysis showed varied associations with explanatory variables between "relief" and the "interest" or "intention post-presentation." The association between "interest" and "intention" aligns well with the finding in a previous study [34]. The present study suggests that participants who experienced increased "interest" and "intention toward overall preventive measures for COVID-19" owing to the presentation of wastewater surveillance information differed in characteristics from those who felt an enhanced sense of "relief regarding the infection status."

Interest in infection status (post) or intent to engage in overall preventive behavior (post) was significantly and positively associated with interest in COVID-19 (pre) and overall preventive behavior (pre) but not with the interaction items with intervention. This means that although participants who had previously shown more interest in COVID-19 and engaged in preventive behavior were more interested in the infection status or intended to engage in overall preventive behavior post-survey, the presentation of wastewater surveillance-based information had no additional effect on these outcomes.

In contrast, relief regarding infection status (post) was negatively associated with overall preventive behavior (pre) and the interaction term between intervention and interest in COVID-19 (pre). It was also positively associated with the interaction term between the intervention and overall preventive behavior (pre). This suggests that those who had engaged in preventive behavior against COVID-19 were more likely to be concerned about its infection status even after receiving information on the infection status, but the wastewater surveillance data increased their sense of relief. In addition, individuals who were less interested in COVID-19 felt more relief when they received wastewater surveillance information.

The data from wastewater surveillance highlighted in this study provided two primary advantages: first, it allows for early detection as wastewater surveillance information captures more recent infection status compared to clinical surveillance data; second, it ensures representativeness by enabling comparisons with infection status derived from a comprehensive survey conducted until the downgrading of the legal status of COVID-19 [7,8].

The infection status highlighted by the wastewater surveillance data in this study was nearly at its peak; however, it showed no significant fluctuations in the count of infections over the previous 2–3 weeks. This stability may have offered some individuals, particularly those who were less interested in COVID-19, a heightened sense of relief. Their relief may have stemmed from the perceived absence of worsening conditions, validating their indifference. Alternatively, knowledge of this novel surveillance method may have provided comfort. Using wastewater for infection tracking is a new approach, but its public awareness remains limited [20]. Those practicing COVID-19 preventive measures may find reassurance from these data, viewing it as an additional resource for informing their actions.

4.4. Limitations

This study has some limitations. First, although we confirmed that there were no significant differences in individual attributes, such as gender and age, and psychological factors between the control and intervention groups prior to presenting the information, we were unable to verify differences in economic status and occupation.

Second, because the participants were exclusively registered active Yahoo! JAPAN crowdsourcing users, caution is necessary when generalizing the findings.

Third, although the presentation of wastewater surveillance information was sufficient for more than 70 % of the participants to understand the infection status, a qualitative analysis of how they interpreted the data was not fully available. A qualitative survey including interviews would be expected to deepen our knowledge of how the participants interpreted the data.

Fourth, the impact of presenting wastewater surveillance information may vary depending on the infection status. Our study focused on a scenario in which the infection numbers were at their peak, but there were no significant fluctuations in the previous 2–3 weeks. Hence, longitudinal monitoring of the perceptions and behavior of individuals exposed to this information is essential to understand the impact of different infection statuses.

Fifth, regarding the online search of the keyword list, we could not determine the actual intent of the participants. Furthermore, some extracted searches might not have aligned with the study's intended focus because keywords were included even if they contained characters before or after the targeted keywords. We assumed that the increase in the number of participants who conducted online searches was associated with keywords such as "highways" or "bullet trains." Future studies should combine online search analyses with behavioral observations.

The sixth limitation of this study relates to the timeframe of behavioral measurement. We analyzed online search behavior over a one-week period following the presentation of wastewater surveillance information, focusing on the period just before the mid-August vacation season in Japan. While this allowed us to capture immediate changes in travel-related search behaviors, it may not fully reflect longer-term behavioral changes. Our focus on short-term changes in search behavior was designed to capture immediate responses to information in the context of upcoming travel plans. Future studies could benefit from examining both immediate search behavior changes and longer-term behavioral adaptations to afford a more comprehensive understanding of the impact of wastewater surveillance information on public behavior and decision-making processes.

Seventh, the effects of this study, which focused on infection status information derived from wastewater surveillance, showed only a minimal impact on preventive behavior and increased search behavior related to highways. Further research is required to develop more impactful information presentation methods.

5. Conclusions

Using a randomized controlled trial design, this study investigated the perceptions and intentions regarding preventive behavior related to COVID-19 by presenting infection status information from wastewater surveillance. Furthermore, we analyzed the behavioral changes brought about by this information using online search patterns. This is the first study to reveal the effects of wastewater surveillance information on the perceptions of and responses to COVID-19. The main findings of this study are as follows.

- Presentation information on infection status via wastewater surveillance increased the "interest in," "relief regarding," and "intention for overall preventive behavior regarding" COVID-19. However, there was no increase in the "understanding of the infection status" and intention to "wear masks" and "receive the COVID-19 vaccination."
- The characteristics of the participants, where the presentation of wastewater surveillance information triggered a further rise in "interest" or "intention for overall preventive behavior regarding" COVID-19, varied from those feeling an enhanced sense of "relief regarding the infection status." The additional effect of presenting information on "interest" or "intention for overall preventive behavior" was unaffected by prior interest in COVID-19 or overall preventive behavior. In contrast, a heightened sense of "relief" was more prominent among those who already practiced COVID-19 preventive behavior or those who were less interested in COVID-19.
- The presentation of wastewater surveillance information may have led to a slight uptick in online searches, such as for highways pertinent to homecoming during the mid-August vacation season, suggesting participants' behavioral changes.
- The utility of presenting wastewater surveillance information was demonstrated through observations of changes in people's perceptions of and response to infections.

CRediT authorship contribution statement

Michio Murakami: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Shuhei Nomura:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Hiroki Ando:** Writing – review & editing, Resources. **Masaaki Kitajima:** Writing – review & editing, Resources, Funding acquisition.

Notes

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Statements

During the preparation of this manuscript, the authors used DeepL solely for the purpose of the possible improvement of English language expression. The authors created the original texts before using this tool. The authors reviewed and edited the content as needed, after using this tool. Furthermore, the paper was carefully edited by native professional editors. The authors take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Michio Murakami reports a relationship with NJS CO., LTD. that includes: consulting or advisory. Masaaki Kitajima reports a relationship with Shionogi & Co., Ltd. that includes: funding grants. Masaaki Kitajima reports a relationship with AdvanSentinel, Inc. that includes: funding grants. Masaaki Kitajima has patent pending to Shionogi & Co., Ltd.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2025.105224.

Data availability

The authors do not have permission to share data.

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