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Lessons Learned from the COVID-19 Pandemic: A Multigroup Structural Equation Modelling of Underground Space Environment and Users' Health

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Abstract: Due to the inherent limitations of underground spaces, such as the lack of natural ventilation and sunlight, underground space users tend to face more health risks compared with their aboveground counterparts. However, little is known about how the underground environment, users' health, and their associations were impacted by the outbreak of the pandemic. In this study, we investigated and compared the impacts of the general underground environment on regular users' physical and psychological health before and after the pandemic. To achieve this aim, the data from 525 surveys were collected from eleven underground sites, followed by an objective field measurement study conducted at five underground sites in Hong Kong pre- and post-outbreak of the pandemic. The multigroup structural equation modelling results indicated that: (i) surprisingly, the users' satisfaction towards almost all underground environment factors, including greenery, connectivity with the aboveground environment, thermal comfort, ventilation, indoor air quality, acoustic comfort, and lighting, excluding wayfinding, were significantly higher in the post-outbreak period; (ii) the users' health, both physical and psychological, was significantly better in the post-outbreak period; (iii) the impacts of visual comfort on the users' physical and psychological health were significantly greater in the post-outbreak period (critical difference ratio ($|CDR|$) > 1.96); (iv) the impacts of wayfinding, greenery, and acoustic and thermal comfort on the users' physical or psychological health were significant only in the pre-outbreak period ($|CDR|$ > 1.96); (v) the impacts of connectivity on the users' physical and psychological health were significant in both the pre- and post-outbreak periods ($|CDR|$ < 1.96). The findings were further cross-validated using the objective measurement results. With an increasing need to develop healthy underground spaces, the study contributes to the development, design, and management of the underground environment to enhance the users' health in the post-outbreak era.

Keywords: COVID-19 pandemic; physical health; pre- and post-outbreak; psychological health; underground environment



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1. Introduction

Since the emergence of COVID-19, this catastrophic pandemic has spread to over 200 countries and territories, infecting over 542 million people, among whom, more than 6.3 million have died [1]. In the past few years, various anti-pandemic measures have been investigated and implemented in different countries around the world, such as mandatory mask wearing, social distancing, quarantines, lockdowns, and so on. These measures function to alleviate the transmission risks that arise from direct contact (e.g., intimate contact with infected patients or contaminated surfaces). However, recent studies have already proven that the coronavirus can be disseminated through both direct and indirect contact (e.g., transmission through respiratory droplets, airborne droplets, contaminated surfaces, etc.) [2,3]. The abovementioned measures have had limited impact on avoiding the health risks that arise from indirect contact, such as transmission through tiny airborne

droplets, which can remain suspended in the air for a long period of time, potentially covering large areas [4]. These transmission risks that arise from indirect contact would be even higher in environments with a high population density and poor ventilation, where the likelihood of contacting the aerosol containing the virus exhaled by infected individuals increases [5].

Due to the rapidly increasing population and restrictions on urban expansion, underground developments are becoming more and more imperative in various metropolitan cities around the world. In fact, building deep underground is becoming more and more common worldwide: Canada developed PATH, the world's largest underground shopping complex, in 2005 [6]; Japan built the Tokyo Roppongi Hills urban complex in 2003 [7]; Singapore has the world's deepest tunnel system (expected completion in 2025) [8]; Hong Kong has formulated master plans for underground development for selected urban areas in 2018 [9]. For countries facing complicated emergency conditions, such as wars and pandemics, the utilization of underground spaces is even more necessary (e.g., Israeli converted an underground space into a hospital to treat COVID-19 patients [10]).

More and more citizens are required to stay or work in underground spaces, such as shopping malls, pedestrian subway systems, offices, recreational facilities, and so on, for long periods of time during a day. As such, underground spaces that lack a human focus would be detrimental to the public's health. Due to the inherent limitations of underground spaces, such as the lack of natural ventilation and sunlight, more challenges have been faced to maintain users' health when compared with the aboveground built environment, especially during the COVID-19 pandemic. For instance, underground metro systems have been found to influence the prevalence of COVID-19 in high-density cities, such as Hong Kong [11,12]. In fact, the comparatively higher concentration of air pollution (e.g., PM_{2.5}) in crowded underground spaces could render commuters more susceptible to viral infection, as these pollutants could carry virus-laden droplets and may cause community infection [13]. Furthermore, due to the various limitations of underground spaces, social acceptance of staying underground has long been low [12,14]. The disclosure that this environment could be a potential medium for virus transmission may further escalate the public's concerns and anxieties about the health risks that underground space users face.

Faced with the unprecedented challenges brought by the COVID-19 pandemic and the continuously increasing demands to stay and work underground, it is essential to incorporate human factors, such as the well-being and safety of the users of these spaces, into the development of underground spaces. Building users' health relies greatly on the built environment [15,16]. When facing the unprecedented global challenge of protecting building users, especially underground space users, from COVID-19, the role of the health-focused management of the indoor environment becomes even more critical [3,4,17]. The COVID-19 pandemic has changed not only people's lives and work styles, but also the public's concerns about and expectations of the built environment [18,19]. However, little is known about its impacts on the underground environment and human health. Even though various studies have been conducted to examine how to enhance building users' health throughout the pandemic by improving indoor air quality (IAQ), such as windows opening to open spaces or outdoor greenery, enlarged window sizes, balconies, and so on [20,21], these solutions can hardly be adopted in the high-risk underground developments. With the increasing need to develop healthy underground spaces, it is urgent to investigate how the underground environment, users' health, and their associations have been impacted by the COVID-19 pandemic.

While previous studies provided empirical support for the impacts of various environmental factors on users' physical and/or psychological health, most of the studies have focused on the aboveground built environment, ignoring the special characteristics and needs of underground space users. Secondly, the majority of underground space studies are fragmented, focusing only on single or partial factor(s). In reality, underground space users are affected by different environmental factors simultaneously. The significance of

each factor can be affected by any combination of the other factors. For instance, space design is essential for users' orientation in an underground environment, which is critical to one's psychological state. However, its effect is highly dependent on the light level in an environment [22]. Without a holistic investigation, it is unclear which factors have had significant impacts on underground users' health in real situations during and after the pandemic outbreak. Lastly, most of the above pandemic-related studies were conducted after the outbreak. There is a lack of in-depth understanding of the potential changes of the underground environment and users' health from the pre- to post-COVID-19 outbreak period. Hence, targeting regular users in the general underground space, the research aimed to:

- Identify multidimensional underground environment factors;
- Investigate the impacts of the underground environment factors on underground space users' health before and after the pandemic.

The results of the study make substantial theoretical and practical contributions, including the following:

- The study expands the theoretical built environment–quality of life (QoL) model by developing an empirical, integrated underground environment–health model for user's physical and psychological health, before and after the pandemic.
- Underground spaces, building services, and supporting elements significantly affecting users' health before and after the pandemic are unveiled and compared.
- It provides practical recommendations for fostering a health-centric underground environment for the post-pandemic era.

2. Theoretical Framework

According to the built environment–QoL model [23], a built environment generally comprises three main aspects: space management, building services, and supporting elements [24,25], in which space management refers to space design, layout, and circulation, building services enable a building to perform its functions to fulfil users' needs regarding indoor environment quality, and supporting elements serve to meet specific requirements such as hygiene. In fact, the built environment–QoL model was developed for and verified by the aboveground built environment in previous studies (e.g., [23–26]). However, underground space users have specific needs that are different from aboveground users, such as connectivity with the aboveground environment, a higher need for greenery, and so on [27], which are not covered in the model. Furthermore, owing to the particularity of the underground environment, the results and contributions of the research on aboveground buildings are not fully applicable to the underground environment, and thus, there is a need to further develop the knowledge in this area by testing and expanding it to the underground environment [28]. Therefore, in the coming section, underground space management, building services, and supporting elements and their potential influences on users' health in the post-outbreak era are elaborated, followed by the development of a conceptual underground environment–health model.

2.1. Underground Space Management

Due to the intrinsic differences between aboveground and underground spaces, the public may develop a sense of spatial segregation inside an underground environment [29]. An underground space designed with inadequate physical connectivity facilities with the aboveground environment, such as escalators, stairs, lifts, intermediary areas, and so on, can cause users to feel a sense of isolation or even anxiety and emotional exhaustion [12,27]. From the physical health perspective, connectivity facilities can enhance ventilation underground [30] and reduce the risk of airborne transmission [31]. On the other hand, while the wayfinding of users in aboveground developments can be supported by one's exposure to landmarks or views outside windows, underground space users often face difficulties in wayfinding [32], affecting their sense of perceived control [33] and physical and psychological health [12,34]. The role of wayfinding in underground developments can be even more

significant after the COVID-19 outbreak, when the public has increased awareness of social distancing and is more concerned about staying in crowded, enclosed places. According to Khotbehsara, Askarizad, Mehrinejad, Nasab, and Somasundaraswaran [35], the pandemic has brought negative impacts on space users' mobility performance. After the pandemic outbreak, space users experienced a significant amount of confusion and hesitation during the wayfinding process due to insufficient spatial accessibility and legibility. In fact, wayfinding is an essential parameter in spatial configuration and circulation management, which can serve as an important reference to social distancing compliance measures. While it is essential to maintain a state of equilibrium between social distancing and social interactions, wayfinding elements, such as the design of access, the location of entry and exits, indefinite directions, and zoning, are closely associated with the effectiveness of controlling the spread of COVID [36].

2.2. Underground Building Services

Indoor ventilation and air quality are essential in controlling virus transmission during the pandemic [37]. However, the often enclosed nature of underground developments makes natural ventilation challenging, which further causes negative impacts on the IAQ due to difficulties in diluting air contaminants [38]. In fact, several studies have discovered a link between the concentration of indoor air pollutants (e.g., PM2.5, PM10) and the airborne transmission of COVID-19, as pollutant particles are capable of loading and transmitting the virus, especially in enclosed places [39,40]. Wu, Nethery, Sabath, Braun, and Dominici [41] found that long-term exposure to an increase of 1 $\mu\text{g}/\text{m}^3$ PM2.5 concentrations resulted in an 8% increase in the COVID-19 death rate. It was discovered that jammed subways had elevated levels of PM2.5 during the pandemic [13]. On the other hand, the humidity level has also been found to be associated with the spread of COVID-19 [42]. To reduce infection risk, the review and enhancement of HVAC performance, including the air change rate and humidity level, are critical [43,44]. Furthermore, the environmental noise level has been found to influence the incidence and severity of COVID-19 patients [45], by affecting one's immune system [46], sleep quality [47], and psychological stress level [48]. Lastly, the pandemic has, to a certain extent, increased the concerns of the public towards the hygiene of public spaces, especially underground spaces, which has long been regarded as posing higher health risks for the users. Proper light management may help increase people's perception of cleanliness in public space [49].

2.3. Underground Supporting Elements

Due to the spatial separation from the aboveground environment, greenery can be used to satisfy underground users' physical and psychological needs for interaction with nature [50,51]. It has also been found that the incorporation of natural elements in a built environment can alleviate building users' psychological burdens, such as stress, anxiety, and sense of isolation, during the pandemic [52–55]. On the other hand, with the aim of controlling the spread of COVID-19 in built environments, various anti-epidemic hardware (e.g., contactless button sensors in lifts, disinfection coating on lift buttons, hand sanitizers, body sanitizing machines, escalator sanitizers, etc.) and software (e.g., frequent cleaning, occupancy density control, etc.) are becoming indispensable [56–59]. These environment management measures are believed to have an impact not only on the physical health of building users, but also on minimizing the psychological stress caused by the pandemic [60]. Due to the public's stronger concerns about hygiene in underground spaces, it is believed that these hygiene hardware and software are of greater importance in underground developments.

3. Conceptual Underground Environment–Health Model

Based on the built environment–QoL model [23], an extensive literature review on the built environment, the underground environment, users' health, and the latest research on the intimate relationships between the built environment and human health during

the COVID-19 pandemic, a conceptual underground environment–health model was developed, as shown in the literature review box in Figure 1. It is anticipated that a healthy underground space comprises three key elements, namely space management, building services, and supporting elements, which have different influences on the physical and psychological health of underground users before and after the COVID-19 outbreak. Figure 1 also illustrates the research methods adopted in the study, which will be further elaborated in the next section.

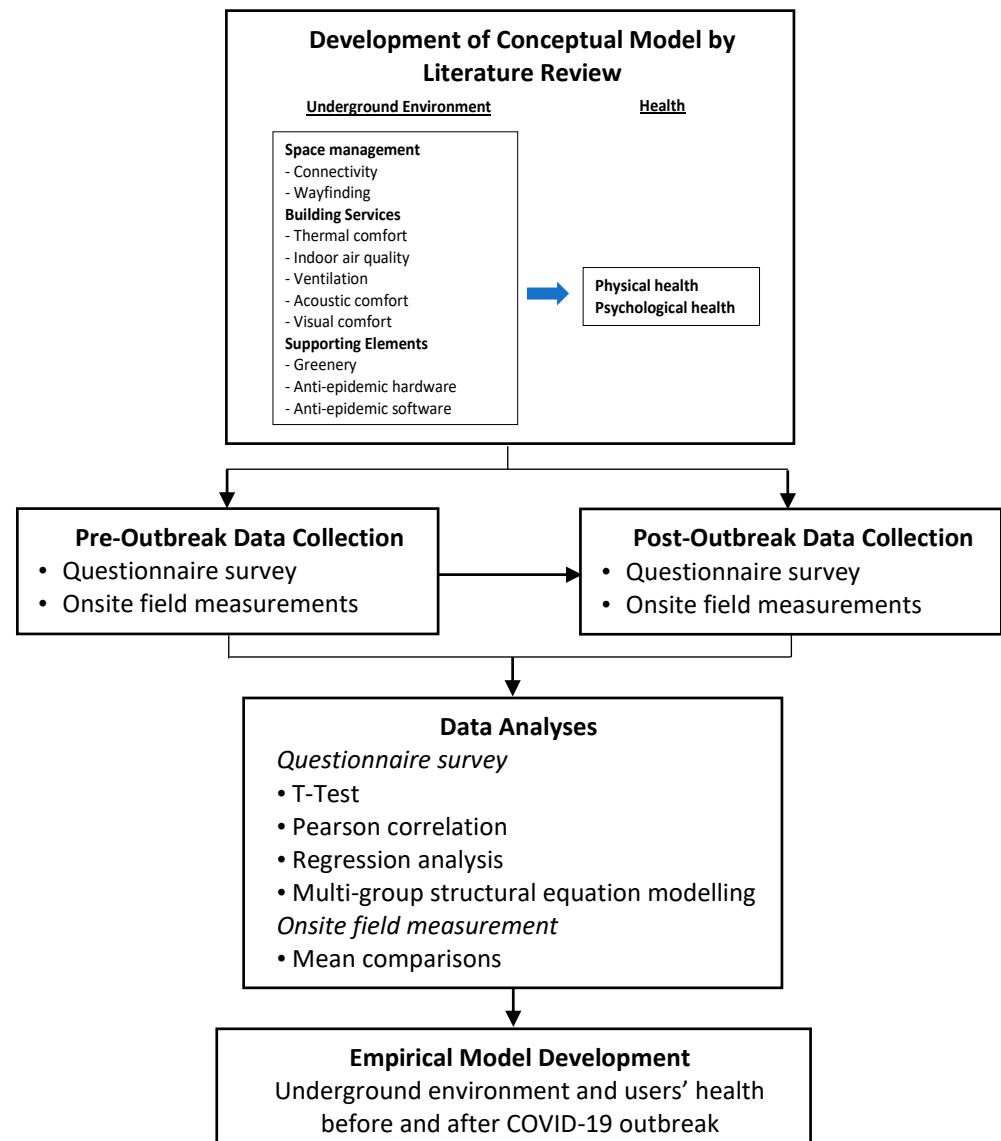


Figure 1. Research framework.

4. Research Methods

To achieve the research objective and validate the conceptual underground environment–health model, a questionnaire survey was developed based on the three aspects of the underground environment, namely space management, building services, and supporting elements, and two health factors, namely physical health and psychological health (see Appendix A).

4.1. Survey Sites

According to Kishii [61], the use of commercial underground developments can mainly be categorized into complex facilities (e.g., shopping malls, office buildings) and

transportation facilities (e.g., subway, parking lots). Since drivers normally stay in a car park for a very short period of time and the number of people required to staff a car park is very low, this study, thus, covered underground shopping malls, subway stations, and underground offices only. Eleven underground sites were deliberately selected to cover different building types (six shopping centers, four subway stations, and one office, which is comparatively rare in Hong Kong), ages (five aged 25 years or above, and six aged under 25 years old), and locations (four on Hong Kong Island (high-density district) and seven in Kowloon (lower-density district)) (see Figure 2).



Figure 2. Eleven underground sites selected.

4.2. Survey Data Collection and Analyses

Visitors of different underground spaces tend to conduct different activities (e.g., passengers rushing to MTR stations vs. customers shopping in an underground mall with a relatively flexible schedule), resulting in different lengths of stay, psychological states, and experiences in an underground environment. To minimize its potential impacts on the study results, purposive sampling was adopted, in which the survey only targeted regular, long-staying employees, such as salespersons, workers, cleaners, and students, but excluded visitors, passengers, and customers, who tend to stay in the underground premises for a comparatively shorter/unstable period of time [62]. Based on an online questionnaire developed using the Qualtrics platform, the survey was administered by research assistants through one-on-one onsite interviews (i.e., the research assistants read out the questionnaire statements and recorded the respondents' answers using the online platform).

Five statistical analyses were then performed to uncover the relationships between the underground environment and users' health. A reliability test with Cronbach's alpha value was first conducted to ensure the measurement scales were reliable (see Section 5.2). To investigate whether significant differences existed between the underground environment and users' health in the pre- and post-outbreak periods, an independent *t*-test was performed (see Section 5.3). Furthermore, Pearson correlation was conducted to examine the relationships between pairs of variables. Then, multiple regression analyses were conducted to discover the predicting effects of a group of underground environment factors on users' physical and psychological health. Based on the results of the correlation and multiple regression analyses, structural equation modelling (SEM) was adopted to investigate and evaluate the multivariate relationships between underground environmen-

tal factors and users' health. The path analysis in SEM was developed to quantify the relationship amongst the latent variables [63]. Furthermore, SEM facilitates multi-group analysis, which tested and compared the structural equation models amongst the pre- and post-outbreak groups [64].

With a sample size of 525 (i.e., 329 in the pre-outbreak period and 196 in the post-outbreak period), the sample to variables ratios (N:p) of the two SEM analyses were 27:1 (pre-outbreak) and 20:1 (post-outbreak), respectively, which are much higher than the minimum requirements of 5:1 and 10:1 as suggested in previous studies [65–68].

4.3. Survey Measurements

The data were collected from the abovementioned eleven underground sites using a questionnaire survey conducted in 2019 (before the COVID-19 outbreak) and 2021 (after the COVID-19 outbreak), respectively. The questionnaire was designed to have three sections, which included background information, users' self-evaluated physical and psychological health symptoms, and satisfaction towards various underground environment factors. For physical and psychological health, the measurement scales of physical-building-related syndromes and emotional exhaustion were adopted [69,70]. The building-related syndromes were evaluated by 11 items related to the frequency of dry eyes, blocked nose, dry throat, headaches, sneezing, breathing difficulties, and so on [71]. Emotional exhaustion was measured using the Maslach Burnout Inventory–Human Services Survey, which covers 8 items including feeling emotionally drained, fatigued, burned out, frustrated, etc. [69]. Respondents were asked to rate the frequency of their health symptoms on a seven-point Likert scale (from 1 = never, to 7 = always). The environment items were measured using an 8-item measurement scale, with each indicating a single aspect of the environment, including greenery, connectivity facilities, wayfinding, thermal comfort, ventilation, IAQ, acoustic comfort, and visual comfort. Respondents were asked to rate their level of satisfaction towards each environmental item using a seven-point Likert scale (from 1 = extremely dissatisfied, to 7 = extremely satisfied). In both the pre- and post-outbreak surveys, the environment factors covered space management (connectivity to aboveground spaces and wayfinding), building services (thermal, ventilation, IAQ, acoustic comfort, and visual comfort), and supporting elements (greenery). After the outbreak, 10 items related to anti-epidemic hardware and software were further added to the survey.

4.4. Onsite Field Measurement Methods

To further validate the survey findings, onsite field measurements were conducted. Firstly, objective field measurements were performed using the intelligent built environment monitor (iBEM). iBEM is a device that includes sensors for measuring temperature (°C), humidity (%), CO₂ (ppm), and illumination (lux). It is used to collect IAQ data and transmit them to a cloud server in real-time [72]. Meanwhile, the acoustic condition of the sites was measured by the noise level (dB) using the ONO SOKKI LA-5110 Precision Integrated Sound Level Meter. Since these indicators deviate from time to time throughout the day, measurements were conducted on an hourly basis, from 9:00 a.m. to 6:00 p.m., during a day. To enable more-precise and -accurate measurements, two measurement locations were selected for each site to cover both high and low occupant density. For subway stations, three height levels in each measurement location were selected at 0.1 m, 0.6 m, and 1.1 m above the floor. For shopping malls, two sub-measurement locations were selected in each measurement point to determine the precise density. For each sub-measurement location, three height levels were selected, similar to that of the subway stations [73].

Furthermore, with reference to the measurement methods developed by De Vries, Van Dillen, Groenewegen, and Spreeuwenberg [74], the quantity and quality of greenery in the selected sites were recorded and rated by an observer during the site visits. In detail, the quantity was assessed with an item running from (1) the environment does not make a very green impression to (7) the environment makes a very green impression. "Green" was broadly defined as all types of visible vegetation, ranging from flower boxes

and individual plants to a view of green walls. The quality of greenery was assessed with variation, maintenance, orderly arrangement, and general impression (De Vries, Van Dillen, Groenewegen, and Spreeuwenberg [74]). All quality items were again scored on 7-point scales. On the other hand, with a focus on space design related to aboveground and underground connections, investigations were performed by recording the number of staircases, lifts, and escalators per 10⁴ square feet, the presence and size of an atrium, and the presence of a skylight, if any. Similarly, the wayfinding system was determined by the variation, maintenance, and general impression of the signage, orientation cue, map, etc., using a 7-point scale.

5. Analyses and Findings

5.1. Demographics of Survey Respondents

A total of 525 valid samples were gathered, among which 329 samples were collected before the COVID-19 outbreak, while 196 samples were collected after the outbreak. In both the pre- and post-outbreak datasets, most respondents were female (pre-outbreak: 61.7%; post-outbreak: 79.1%). In terms of type of industry, the majority of respondents worked in underground shopping malls (pre-outbreak: 54.7%; post-outbreak: 60.7%), followed by subways (pre-outbreak: 36.5%; post-outbreak: 29.6%), and offices (pre-outbreak: 8.8%; post-outbreak: 9.7%). In terms of age distribution, most of the respondents were aged 18 to 39 (pre-outbreak: 34.3%; post-outbreak: 76%), followed by 40 to 49 (pre-outbreak: 31.0%; post-outbreak: 13.8%), 50 to 59 (pre-outbreak: 25.8%; post-outbreak: 6.6%), 60 to 69 (pre-outbreak: 7.6%; post-outbreak: 2.6%), and others (pre-outbreak: 1.2%; post-outbreak: 1.0%).

5.2. Reliability Test

To evaluate the reliability of the measurement scales used for physical and psychological health, their Cronbach's alpha values were examined (a measurement scale is considered reliable only if its Cronbach's alpha value is higher than 0.60 [75]). As shown in Table 1, measurement items for physical health were reliable in both the pre- and post-outbreak periods ($\alpha > 0.6$). However, the Cronbach's alpha value for psychological health was 0.445 in the pre-outbreak period ($\alpha < 0.6$). To ensure internal consistency, an item, "feel used up", was removed from both periods. The Cronbach's alpha value for psychological health then increased to 0.629 and 0.794, respectively, for the pre- and post-COVID periods ($\alpha > 0.6$). Furthermore, the Cronbach's alpha tests on anti-epidemic software and hardware indicated that both scales were reliable ($\alpha > 0.6$).

Table 1. Reliability analysis results.

Factors	Measurement Items	Cronbach's Alpha Values	
		Pre-Outbreak	Post-Outbreak
Physical health	Dry eyes	0.787	0.845
	Itchy or watery eyes		
	Blocked or stuffy nose		
	Runny nose		
	Dry throat		
	Lethargy or tiredness		
	Headache		
	Dry, itchy, or irritated skin		
	Sneezing		
	Breathing difficulties		
	Insomnia		

Table 1. Cont.

Factors	Measurement Items	Cronbach's Alpha Values	
		Pre-Outbreak	Post-Outbreak
Psychological health	Feel emotionally drained	0.629	0.794
	Feel fatigued		
	Feel burned out		
	Job is hardening me emotionally		
	Feel frustrated		
	Feel working too hard		
Anti-epidemic software	Feel I am at the end of my rope	-	0.780
	Hygiene facilities satisfaction		
	Temperature checking in entrance		
	Temperature checking in common area		
	Temperature checking in office/shop		
	Hygiene education satisfaction		
Anti-epidemic hardware	Crowd control satisfaction	-	0.817
	Hand sanitizer in entrance		
	Hand sanitizer in common area		
	Hand sanitizer in office/shop		
	Disinfection products satisfaction		

Due to the concrete and unidimensional nature of the environment indicators and the mixed background of the sampled population, single-item scales were adopted as a legitimate approach to operationalize the underground environment constructs in the study [76]. This approach has been widely adopted in relevant built environment studies [77,78]. In addition to the reliability test, normality is guaranteed for factors in the conceptual model with acceptable skewness and kurtosis values according to [79].

5.3. Independent *t*-Test and Factor Comparisons

(1) Pre- and Post-Outbreak Comparisons:

To investigate whether statistically significant differences existed between users' health and satisfaction towards various underground environment elements before and after the outbreak, an independent *t*-test was conducted. As shown in Table 2, the results indicated that, interestingly, after the COVID-19 outbreak, underground users had significantly higher levels of satisfaction with regard to the underground environment factors in general, except for wayfinding. To determine the magnitude of the difference, the eta-squared values were calculated. The results indicated that the differences in the means were large for visual comfort (eta-squared = 0.377), moderate-to-large for IAQ (eta-squared = 0.115), and small-to-moderate for other environment factors (eta-squared < 0.100). In terms of health indicators, the results revealed that respondents experienced statistically lower levels of physical and psychological health symptoms after the outbreak. The magnitudes of significance were large, with eta-squared larger than 0.100.

In addition, the COVID-19 outbreak is also believed to have brought changes to employees' work pattern, such as working hours in the underground space [80]. The number of hours an individual stays underground may have an impact on their health and perceptions towards the underground environment. Hence, an independent *t*-test was performed to investigate whether significant differences existed between respondents' working hours before and after the pandemic outbreak. The result revealed a significant difference ($p < 0.001$). As such, the variable of working hour in the underground space

was controlled for in the following multiple regression analyses and structural equation modelling.

Table 2. Independent *t*-test for underground environment, health, and working hours of underground space users.

		Pre-Outbreak		Post-Outbreak		t	Sig.	Eta-Squared
		Mean	Std	Mean	Std			
Underground environment	Greenery	2.277	1.575	3.026	1.517	−5.342	0.000	0.052
	Connectivity facilities	4.076	1.576	4.689	1.867	−3.849	0.000	0.030
	Wayfinding	4.185	1.318	3.612	1.843	3.811	0.000	0.032
	Thermal comfort	3.456	1.237	4.342	1.519	−6.913	0.000	0.092
	Ventilation	3.407	1.106	4.061	1.538	−5.204	0.000	0.057
	IAQ	3.176	1.520	4.301	1.528	−8.185	0.000	0.114
	Acoustic comfort	3.274	1.035	4.056	1.903	−5.308	0.000	0.066
	Visual comfort	3.210	1.046	5.128	1.410	−16.525	0.000	0.377
Health	Physical health	3.651	0.797	2.397	0.925	16.402	0.000	0.340
	Psychological health	2.926	0.637	2.243	1.003	8.553	0.000	0.148
Working hours in the underground space		1.635	1.262	2.765	1.622	−8.361	0.000	0.132

Note: Underground environment satisfaction scale: 1—very dissatisfied; 7—very satisfied.; health symptom scale: 1—never; 7—always; working hours in underground space: 1—>54; 2—45–53; 3—36–44; 4—27–35; 5—18–26; 6—9–17; 7—<8; *italic coefficients*: significantly higher ($p < 0.001$).

Health was the key dependent factor in this study, and it can be highly associated with age. To further investigate the distribution of respondents' health levels in different age groups before and after the pandemic, Figures 3 and 4 were developed. The results showed that respondents' physical and psychological health were both higher in the post-outbreak period. The pattern was the same amongst all age groups, which echoes the results of the independent *t*-test.

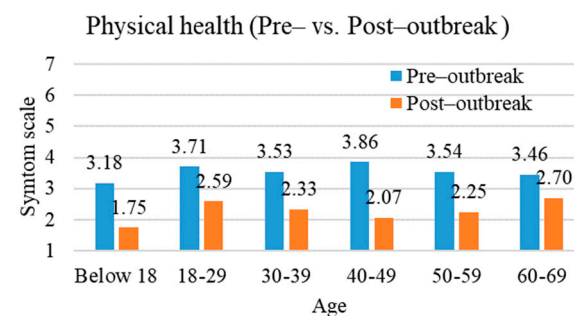


Figure 3. Pre- and post-pandemic physical health of underground space users by age.

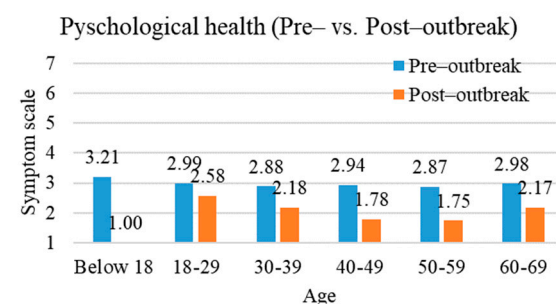


Figure 4. Pre- and post-pandemic psychological health of underground space users by age.

(2) Comparisons between different types of underground spaces:

To investigate whether statistically significant differences existed between different types of underground space, a one-way analysis of variance (ANOVA) was conducted for both underground environment factors and users' health in three types of underground spaces (i.e., shopping malls, subways, offices), as shown in Table 3 and Figure 5. The results revealed that, when compared with subway stations and/or offices, the satisfaction levels of users in underground shopping malls were significantly higher in terms of greenery ($F = 33.296$, $p < 0.01$), thermal comfort ($F = 15.188$, $p < 0.01$), and ventilation ($F = 9.293$, $p < 0.01$). However, it should be noted that there was no significant difference in both the physical ($p > 0.05$) and psychological ($p > 0.05$) health of the users amongst the three types of underground spaces.

Table 3. One-way between-groups ANOVA for underground environment factors and health satisfaction in different underground spaces.

Factors	One-Way between-Groups ANOVA						Post Hoc Test for Factors with Significant Diff. Satisfaction.			
	Type	Mean	SD	F (ANOVA)	Sig. (ANOVA)	Sig. (Levene)	Type Group	Mean diff.	SE	Sig.
1. Physical health	Subway	3.219	0.997	1.349	0.260	0.060				
	Shopping mall	3.136	1.083							
	Office	3.423	0.849							
	Total	3.183	1.041							
2. Psychological health	Subway	2.615	0.877	2.470	0.086	0.404				
	Shopping mall	2.669	0.858							
	Office	2.967	0.718							
	Total	2.671	0.859							
3. Greenery	Subway	1.966	1.356	33.296	0.000	0.000	Shopping mall Office	−1.025 * 1.362 *	0.142 0.268	0.000 0.000
	Shopping mall	2.990	1.620							
	Office	1.629	1.060							
	Total	2.556	1.594							
4. IMA	Subway	4.239	1.653	0.239	0.787	0.001				
	Shopping mall	4.347	1.797							
	Office	4.257	1.221							
	Total	4.305	1.715							
5. Wayfinding	Subway	4.040	1.412	0.305	0.737	0.055				
	Shopping mall	3.946	1.654							
	Office	3.857	1.396							
	Total	3.971	1.558							
6. Thermal comfort	Subway	3.403	1.399	15.188	0.000	0.182	Shopping mall Office	−0.654 * 0.772 *	0.130 0.245	0.000 0.005
	Shopping mall	4.057	1.388							
	Office	3.286	1.152							
	Total	3.787	1.414							
7. IAQ	Subway	3.386	1.430	2.596	0.076	0.000				
	Shopping mall	3.726	1.621							
	Office	3.486	2.267							
	Total	3.596	1.616							
8. Ventilation	Subway	3.307	1.299	9.293	0.000	0.963	Shopping mall	−0.521 *	0.123	0.000
	Shopping mall	3.828	1.297							
	Office	3.800	1.346							
	Total	3.651	1.322							
9. Noise	Subway	3.557	1.321	0.593	0.553	0.035				
	Shopping mall	3.599	1.541							
	Office	3.314	1.549							
	Total	3.566	1.470							
10. Visual comfort	Subway	4.091	1.370	2.215	0.110	0.000				
	Shopping mall	3.873	1.627							
	Office	3.571	0.948							
	Total	3.926	1.512							

Note: * $p < 0.05$; Bold figures are significant between-group differences.

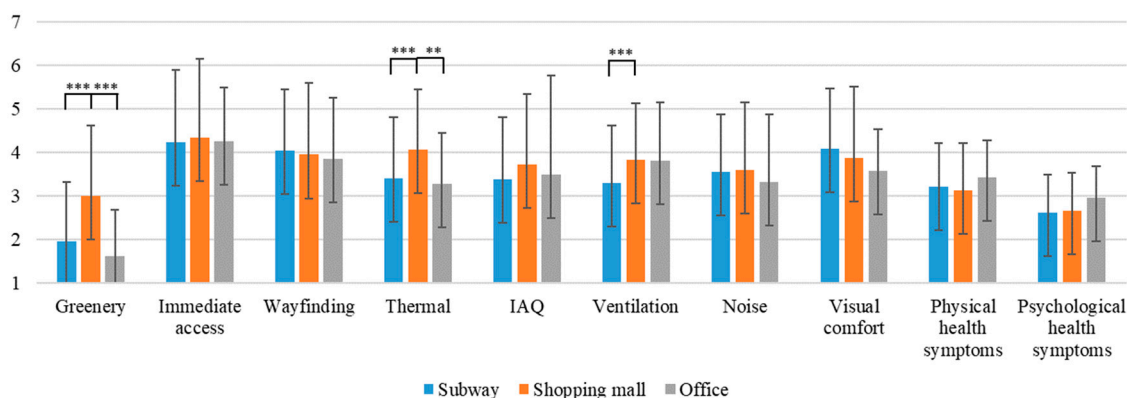


Figure 5. Comparison of underground environment factors and health satisfaction in three underground spaces (** $p < 0.01$; *** $p < 0.001$).

Different types of underground spaces have different usages. While users generally visit/stay in underground subways or offices due to basic necessity, users of shopping malls have relatively more freedom in mall selection. Therefore, creating a pleasant environment is one of the business strategies of the shopping mall managers to draw visitors. It is thus reasonable that shopping malls perform better in greenery, thermal comfort, and ventilation. However, there is no evidence that these between-space-type differences have any impacts on users' health (no significant difference in either physical or psychological health). Perhaps the three significantly different environmental factors are not critical in predicting underground users' health, especially in the post-outbreak era (refer to Section 5.6 for a more detailed analysis). Further studies are recommended to investigate in-depth whether the impacts of the underground environment on users' health are the same for different types of underground spaces.

5.4. Pearson Correlation Analysis

To explore the inter-relationship between the underground environment and health indicators, Pearson correlation analysis was conducted for both the pre- and post-outbreak datasets, as shown in Table 4. Amongst the pre-outbreak responses, both physical and psychological health symptoms were negatively correlated with greenery, connectivity facilities, thermal comfort, ventilation comfort, IAQ, and noise level and positively correlated with wayfinding comfort ($p < 0.001$). Amongst the post-outbreak data, the physical health of underground users was negatively correlated with connectivity facilities, thermal comfort, ventilation, IAQ, noise, visual comfort, anti-epidemic hardware, and anti-epidemic software ($p < 0.01$ or $p < 0.05$) and the psychological health of underground users was negatively correlated with greenery, connectivity facilities, wayfinding, ventilation, and visual comfort ($p < 0.01$ or $p < 0.05$).

Table 4. Pearson correlation of underground environment and user health.

	Greenery	Connectivity Facilities	Wayfinding	Thermal Comfort	Ventilation	IAQ	Acoustic Comfort	Visual Comfort	AE Hardware	AE Software	Physical Health	Psycho. Health
Greenery	1.000	0.073	0.086	0.110	0.176 *	0.078	0.049	0.214 **	0.117	0.181 *	−0.072	−0.188 **
Connectivity facilities	0.376 **	1.000	0.419 **	0.191 **	0.119	0.132	0.143 *	−0.018	0.043	0.054	−0.161 *	−0.185 **
Wayfinding	−0.339 **	−0.572 **	1.000	0.198 **	0.098	0.133	0.000	0.011	−0.056	0.059	−0.036	−0.142 *
Thermal comfort	0.362 **	0.134 *	−0.196 **	1.000	0.596 **	0.636 **	0.206 **	0.181 *	0.203 **	0.317 **	−0.153 *	−0.124
Ventilation	0.353 **	0.316 **	−0.376 **	0.447 **	1.000	0.636 **	0.216 **	0.308 **	0.055	0.253 **	−0.223 **	−0.197 **
IAQ	0.182 **	0.216 **	−0.223 **	0.430 **	0.445 **	1.000	0.214 **	0.188 **	0.175 *	0.350 **	−0.191 **	−0.110
Acoustic comfort	0.137 *	0.094	−0.250 **	0.305 **	0.529 **	0.265 **	1.000	0.100	0.285 **	0.287 **	−0.175 *	−0.092
Visual comfort	−0.241 **	−0.076	0.054	−0.093	−0.008	−0.085	0.150 **	1.000	0.316 **	0.332 **	−0.285 **	−0.284 **
Anti-epidemic (AE) hardware	-	-	-	-	-	-	-	-	1.000	0.719 **	−0.221 **	−0.094
Anti-epidemic (AE) software	-	-	-	-	-	-	-	-	-	1.000	−0.233 **	−0.106
Physical health	−0.475 **	−0.516 **	0.562 **	−0.358 **	−0.474 **	−0.300 **	−0.356 **	0.087	-	-	1.000	0.384 **
Psychological health	−0.292 **	−0.306 **	0.288 **	−0.390 **	−0.238 **	−0.268 **	−0.207 **	0.092	-	-	0.419 **	1.000

* $p < 0.05$; ** $p < 0.01$; Under diagonal line: pre-outbreak data; above diagonal line: post-outbreak data

5.5. Regression Analyses

Multiple regression analyses were then further performed to investigate the predictive effects of a group of underground environment factors on the physical and psychological health of users before and after the COVID-19 outbreak. Using the pre-outbreak data, the regression analysis results are summarized in Table 5. Prior to the COVID-19 outbreak, the physical health of underground users was predicted by greenery (-0.201 , $p < 0.001$), connectivity facilities (-0.247 , $p < 0.001$), wayfinding (0.259 , $p < 0.001$), thermal comfort (-0.116 , $p < 0.05$), and acoustic comfort (-0.141 , $p < 0.05$). The model explained 53.7% of the variance of underground users' physical health. Psychological health was negatively predicted by connectivity facilities (-0.263 , $p < 0.001$) and thermal comfort (-0.351 , $p < 0.001$). The model explained 22.9% of the variance of psychological health.

Table 5. Multiple regression analyses using pre-outbreak data.

	Model	Beta	Std	Standard Beta	t	Sig.	R	R ²	ANOVA (Sig.)
Physical health ← underground environment factors									
1	(Constant)	4.500	0.272	-	16.521	0.000	0.733	0.537	0.000
	Greenery	−0.102	0.023	−0.201	−4.507	0.000			
	Connectivity facilities	−0.125	0.025	−0.247	−5.079	0.000			
	Wayfinding	0.157	0.029	0.259	5.326	0.000			
	Thermal comfort	−0.075	0.029	−0.116	−2.621	0.009			
	Acoustic comfort	−0.109	0.035	−0.141	−3.091	0.002			
Psychological health ← underground environment factors									
2	(Constant)	3.882	0.124	-	31.233	0.000	0.478	0.229	0.000
	Connectivity facilities	−0.106	0.020	−0.263	−5.352	0.000			
	Thermal comfort	−0.181	0.025	−0.351	−7.134	0.000			

Note: The analyses were controlled for respondents' age, gender, smoking habit, chronic illness, long-term medication, and working hours in the underground space; ← represents the effect from independent variables to dependent variables.

Multiple regression analyses were then performed using the collected post-outbreak data. As shown in Table 6, the physical health of underground users was negatively associated with visual comfort (-0.259 , $p < 0.001$) and connectivity facilities (-0.179 , $p < 0.05$). The model explained 18.9% of the variances of physical health. On the other hand, visual comfort (-0.258 , $p < 0.001$) and connectivity facilities (-0.189 , $p < 0.05$) were negatively associated with psychological health with 20.5% of the variances explained.

Table 6. Multiple regression analyses using post-outbreak data.

	Model	Beta	Std	Standard Beta	t	Sig	R	R ²	ANOVA (Sig)
Physical health ← underground environment factors									
1	(Constant)	1.617	0.563	-	2.872	0.005	0.435	0.189	0.000
	Connectivity facilities	-0.089	0.032	-0.179	-2.745	0.007			
	Visual comfort	-0.169	0.044	-0.259	-3.891	0.000			
Psychological health ← underground environment factors									
2	(Constant)	3.143	0.581	-	5.406	0.000	0.453	0.205	0.000
	Connectivity facilities	-0.101	0.035	-0.189	-2.925	0.004			
	Visual comfort	-0.183	0.047	-0.258	-3.929	0.000			

Note: The analyses were controlled for respondents' age, gender, smoking habit, chronic illness, long-term medication, and working hours in the underground space; ← represents the effect from independent variables to dependent variables.

5.6. Multi-Group Structural Equation Modelling

To validate the findings of the regression analysis [25], to further explore the integrated structural associations between underground environment factors [81] and physical and psychological health, and to examine whether statistically significant differences existed between the identified underground environment–health associations of the pre- and post-outbreak data, multi-group structural equation modelling (SEM) was further performed using AMOS Version 28, a statistical software for SEM analysis by extending standard multivariate analysis approaches [82]. The model was firstly constructed by fully connecting the underground environmental factors and health indicators ($\chi^2 = 30.653$; $\chi^2/\text{df} = 15.326$; GFI = 0.989; AGFI = 0.386; CFI = 0.977; NFI = 0.977; RMSEA = 0.166; and SRMR = 0.0152). Then, the insignificant paths shown both in the pre- and post-outbreak were removed. The fit indices of the resulting model indicated that the multi-group SEM possessed robust data ($\chi^2 = 10.533$; $\chi^2/\text{df} = 1.755$; GFI = 0.995; AGFI = 0.940; CFI = 0.994; NFI = 0.987; RMSEA = 0.039; and SRMR = 0.0218). The χ^2/df was less than 3, which indicated the model's adequacy. The other model fit indices, including the GFI, AGFI, CFI, and NFI, were all greater than 0.9, which indicated a satisfactory model fit. In addition, the RMSEA and SRMR were both less than 0.05, indicating a good fit [83].

Table 7 and Figure 6 present and compare the resulting path coefficients between the pre- and post-outbreak data. With reference to Jang and Kim (2018), the critical difference ratios (CDRs) between the parameters were calculated using pairwise parameter comparisons in multi-group SEM. A path coefficient was considered significantly different between groups if the absolute CDR value was greater than 1.96 [84]. As shown in Table 6, the impacts of visual comfort on the users' physical and psychological health were significantly greater in the post-outbreak period ($|\text{CDR}| > 1.96$). The impacts of greenery, wayfinding, and acoustic and thermal comfort on users' physical or psychological health were significant only in the pre-outbreak period ($|\text{CDR}| > 1.96$). The impacts of connectivity on users' physical and psychological health were significant in both the pre- and post-outbreak periods ($|\text{CDR}| < 1.96$).

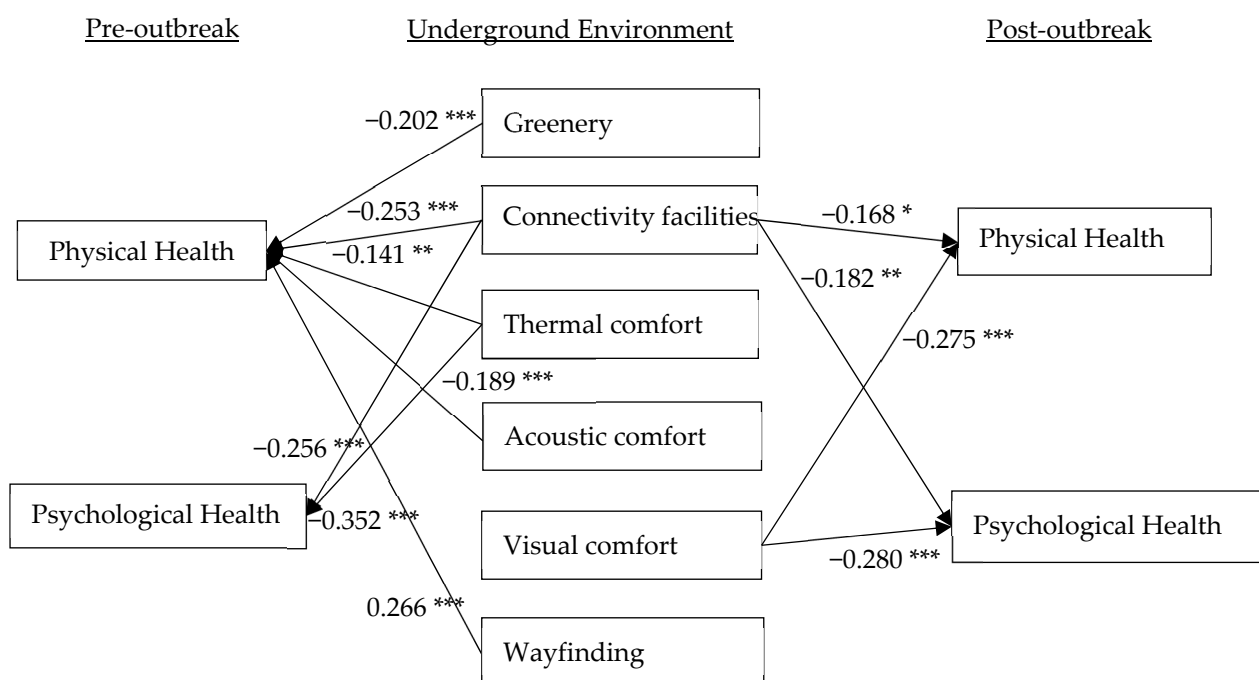


Figure 6. Structural relationships between underground environment and users' health before and after the COVID-19 outbreak (refer to Table 7 for the details of the path coefficients); * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table 7. Path coefficient between pre- and post-outbreak data.

Endogenous Variables	Exogenous Variables	Pre-Outbreak (<i>n</i> = 329)			Post-Outbreak (<i>n</i> = 196)			CDR
		Standard Estimate	C.R.	<i>p</i>	Standard Estimate	C.R.	<i>p</i>	
Physical health	Greenery	−0.202	−4.415	0.000	0.041	0.621	0.535	2.747 *
	Connectivity	−0.253	−5.141	0.000	−0.168	−2.263	0.024	0.986
	Wayfinding	0.266	5.423	0.000	0.065	0.916	0.360	−2.757 *
	Thermal	−0.141	−3.211	0.001	−0.067	−0.951	0.342	0.955
	Acoustic	−0.189	−4.449	0.000	−0.102	−1.546	0.122	2.088 *
	Visual	0.021	0.502	0.616	−0.275	−3.953	0.000	−3.543 *
Psychological health	Connectivity	−0.256	−5.184	0.000	−0.182	−2.657	0.008	0.130
	Thermal	−0.352	−7.126	0.000	−0.039	−0.555	0.579	2.961 *
	Visual	0.039	0.799	0.424	−0.280	−4.09	0.000	−3.903 *

* |CDR| > 1.96; significant difference between pre- and post-outbreak data. Note: The analyses were controlled for respondents' age, gender, smoking habit, chronic illness, long-term medication, and working hours in the underground space.

5.7. Objective Field Measurement Results

Previous studies indicated that human comfort in a built environment can be affected by various psychological parameters, such as the individuals' desired condition [85] and environmental beliefs [86]. To cross-validate the questionnaire survey results, objective field measurements were further conducted for both the pre- and post-outbreak periods. Based on the eleven underground sites covered in the survey study, five were further selected for the field study, which enabled a good mix of building types, age, design, and size [87,88], as shown in Table 8.

Table 8. Underground sites for onsite field measurements.

Sites	Underground Type	Age	Enclosure	Area Size (sq ft)	Physical Health	Psychological Health
S1	Subway station	39	Fully	>20,000	3.953	3.319
S2	Shopping center	25	Fully	>20,000	3.767	3.190
S3	Subway station	21	Partially	>20,000	3.623	2.957
S4	Subway station	40	Fully	>20,000	3.377	2.867
S5	Shopping center	24	Partially	>20,000	2.433	2.629

Note: Likert scale for physical and psychological health adopted in the survey study (1—always (poor health) to 7—never (good health)).

The measurement results of the pre- (blue) and post- (orange) pandemic periods are illustrated in Figure 7. The red arrows on the right-hand side of each figure represent the upper limits of a corresponding standard, and the green arrows represent the lower limits. Firstly, a temperature between 20 and 25.5 °C can be classified as the excellent class, and a temperature below 25.5 °C can be classified as the good class under the guidelines adopted in Hong Kong (where the cases were based) [89]. The result showed that the temperature of all sites in the post-outbreak period was lower than that measured in the pre-outbreak period. The results were similar for the CO₂ concentration. All five sites had reduced CO₂ concentrations in the post-outbreak period, with all being categorized as “excellent” (less than 800 ppmv) [89]. The relative humidity levels measured in the post-outbreak period were also generally lower than those of the pre-outbreak period (nearly all sites fell into the excellent class ranging from 40 to 70%) [89]. According to the Hong Kong Green

Building Council (2019), a built environment with an indoor noise level lower than 50 dB in office areas and 55 dB in common areas would be given a credit under the Building Environmental Assessment Method. As illustrated in Figure 7, the sites all exceeded the recommended noise level, whether before or after the pandemic outbreak. The changes in the noise levels were also inconsistent amongst the sites. Similarly, light levels within 200 and 500 lux are considered as comfortable [90]. While there were sites with enhanced light levels after the pandemic outbreak, two of the sites still fell outside the comfortable level after the pandemic outbreak. The changes in light levels were also inconsistent amongst the sites.

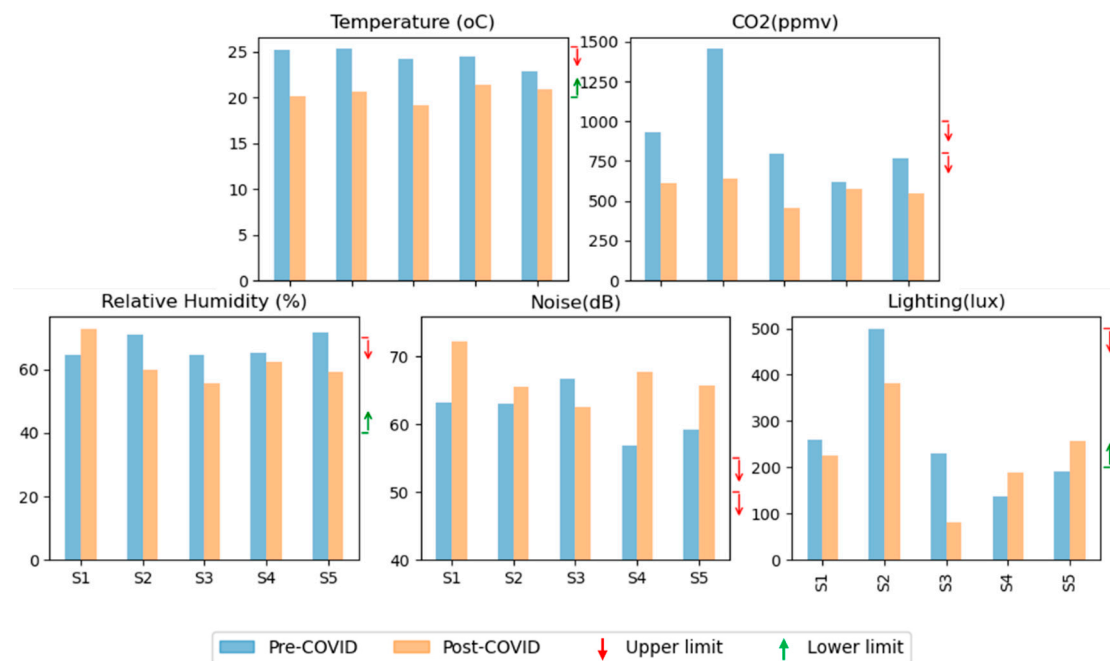


Figure 7. Field measurement results for Underground Sites S1 to S5.

As shown in Figure 8, with reference to the auditing tool developed by [74], the greenery level was slightly enhanced in two of the sites, but remained unchanged in the rest in the post-outbreak period. Wayfinding and connectivity were slightly enhanced in some of the sites after the pandemic's outbreak.

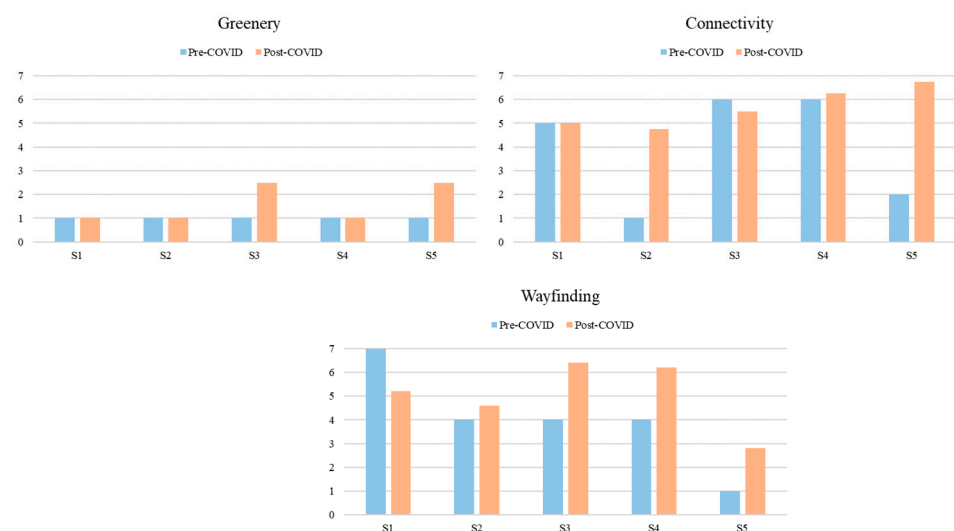


Figure 8. On-site observations for Underground Sites S1 to S5.

5.8. Other Important Health-Centric Underground Environment Elements in the Post-Outbreak Era

To further identify key underground environment elements, which, from the end-users' perspective, would have an impact on their health in underground developments after the COVID-19 outbreak, survey respondents were invited to answer an open-ended question: "In your opinion, how can underground environment be enhanced to lower users' health risks under COVID-19?" In total, 85 responses were collected. They were categorized into seven areas, namely toilet management, hygiene facilities, HVAC system, personal hygiene monitoring, crowd management, hygiene education, and others (in descending order of frequency; refer to Table 9).

Table 9. Other important health-centric underground environment elements in the post-outbreak era.

Underground Environment Elements	Freq.
1. Toilet management:	
- Automatic toilet door for avoiding frequent touching	27
- Lack of elevated ventilation and fresh air supply in the queuing area (outside toilet)	
- Poor hygiene inside toilet	
2. Hygiene facilities:	
- Automatic or touch-less button in areas that are frequently touched	18
- Cleaning robot for enhancing disinfection efficiency	
- More hand sanitizers and disinfection products to cater to high occupancy	
- Lack of adequate garbage bins	
3. HVAC system:	
- Re-design of the existing HVAC system to add disinfection functions	17
- Lack of fresh air, high temperature, and odor in underground car park	
- Ventilation is insufficient (in general underground area)	
4. Personal hygiene monitoring:	
- Lack of supervision of mask wearing	8
- Underground entrance temperature checking should be enhanced	
5. Crowd management:	
- Too crowded in underground areas	6
- Crowd control	
6. Hygiene education:	
- Educate users on better personal hygiene, mask usage, and waste management	4
7. Others:	
- Waste management	5
- Introduce natural lighting for mental health	
- Health of underground users should be a concern regardless of the pandemic	
Total:	85

6. Discussion

6.1. Changes in Levels of Underground Environment and Health after COVID-19 Outbreak

Underground space users' physical and psychological health have both improved significantly after the outbreak of COVID-19 (refer to Table 2). The results partly echo the findings of some previous studies that found that the physical health of citizens improved after the COVID-19 outbreak (e.g., [91,92]). To a certain extent, the lockdowns in some countries or the social distancing and work-from-home arrangements in Hong Kong brought about by the pandemic have allowed citizens to take better care of their physical health during this period. For instance, a previous study found that those who rarely exercised before the lockdown tended to increase their exercise frequency during the lockdown [93]. On the other hand, with regard to psychological health, previous studies

generally found that the mental health of participants was worsened by the pandemic (e.g., [55,91,94–97]). However, in this study, the psychological health of the participants was found to have improved after the pandemic. This can be explained by the different pandemic levels and, thereby, the response policies adopted in these research areas. While most previous studies were conducted in areas with comparatively more serious pandemic levels, which resulted in lockdowns, the pandemic level in Hong Kong during and before the time of the post-outbreak data collection was comparatively less serious. Instead of lockdowns, the Hong Kong government adopted social distancing measures and work-from-home management for the public sector. As such, compared with the participants of previous studies who had to be locked up at home for a certain period, participants in the current study enjoyed a slower pace of life, enabling them to have increased personal time and family time and maintain a certain level of social connection with others (depending on the social distancing rules). The change from a fast-paced lifestyle to a slower one had a positive impact on the psychological health of the participants in this study.

Furthermore, participants' satisfaction towards most of the underground environment factors (i.e., greenery, connectivity facilities, thermal comfort, ventilation, IAQ, acoustic comfort, and visual comfort) was found to be enhanced after the COVID-19 outbreak. This significant change can be explained by three forces faced by underground environment professionals, namely governance, market pull, and technology push. For instance, after the COVID-19 outbreak, the Hong Kong government has tightened the requirements on air purifiers or air change per hour in eateries so as to reduce the spread of and lower the risk of exposure to COVID-19 [98]. This policy not only leads to the immediate action of underground environment professionals who are managing premises with dining areas, but also drives leading firms in the market to review and enhance the indoor environment and facilities inside their premises as a whole, in order to rebuild/boost the confidence of tenants, customers, and visitors. In the review process, firms also inquired about various innovative technologies, such as cleaning robots, automated face mask detection systems, social-distancing-monitoring systems, and so on, which further enhanced the effectiveness of COVID-19 transmission control [57,58].

It is interesting to find that wayfinding was the only environment factor with a significantly lower satisfaction level after the COVID-19 outbreak. In contrast with the users of the aboveground indoor built environment, underground space users cannot rely on outside-the-window landmarks or environments to assist in the creation of a mental image that improves wayfinding in the often-confined underground spaces. Wayfinding is particularly important for underground users, especially in the post-outbreak period when the public is aware of the health risks brought by unnecessary social contact. Due to the fear of exposure to coronavirus, crowded areas can cause panic to space users [35]. While clear and direct wayfinding systems could enable effective social distancing, a complex and unclear wayfinding system may result in the unwanted crossing of users [99]. Previous studies have indicated the effects of underground spaces on users' social behaviors (e.g., criminal or helping behaviors [100]). To facilitate underground space users' social distancing behaviors, which is essential for controlling the COVID-19 outbreak, underground spaces should be carefully configured to enable adequate space (both between shops and between visitors), minimum/one-way circulation paths, and effective signage/zoning systems (in terms of the size, color, and location of the signage).

On the other hand, the COVID-19 pandemic has impacted building users' mobility [74] and work patterns (refer to Section 5.3), which may result in the deterioration of their orientation ability. Spatial orientation is regarded as a feeling associated with one's knowing of a place [101]. For instance, if an individual is familiar with a place, one's spatial orientation in that environment would be stronger [102]. The spatial disorientation of an underground space can cause unpleasant and difficult wayfinding experiences for space users. Furthermore, even though a physical space may have remained unchanged after the pandemic outbreak, changes in circulation rules, social distancing, and crowd management may still create challenges to underground space users' spatial orientation and wayfinding.

6.2. Underground Environment Factors Influencing Users' Health after COVID-19 Outbreak

As shown in the resulting model, after the outbreak, while connectivity facilities remained a significant factor predicting underground space users' physical and psychological health, visual comfort, which was not significant in the pre-outbreak model, became a significant predicting factor of both the physical and psychological health of underground users, respectively. According to Molenaar and Hu [49], a feeling of safety in a built environment is based on three aspects, namely quality of overview (related to indoor lighting and building users' visual comfort), easy escape possibilities (related to connectivity facilities), and freedom of location and route. In this present study, while respondents had no mobility restrictions, the two factors in the safety model, namely quality of overview and easy escape possibilities, can be used to explain the two significant factors found in the post-outbreak model, i.e., visual comfort and connectivity facilities.

6.2.1. Visual Comfort and Users' Health after COVID-19 Outbreak

In fact, occupants' visual comfort is enabled and determined by lighting in an indoor environment [103]. The enclosed nature of underground spaces makes lighting essential to ensure underground space users' health [104]. Due to the changes of people's mobility patterns caused by the pandemic (i.e., decrease in outdoor social interaction and increase in staying indoors for work and personal life), the importance of lighting and visual comfort on building users' health is even higher [105], let alone that of underground space users. On the one hand, artificial lighting, especially those exposed during night time, affects the biological health and COVID-19 risks of building users through its influences on the human immune system and hormone secretion [106]. On the other hand, the fear of COVID-19 exposure in an enclosed underground environment triggers the feeling of being unsafe in users. To reduce uncertainties in an environment, a high quality of overview enabled by an appropriate level of lighting can influence ones' perception of cleanliness, and thus psychological safety, towards an indoor environment [49]. This further explains the findings in this study that, while underground space users' visual comfort had no significant impacts on health before the pandemic, it significantly influenced both users' physical and psychological health in the post-outbreak era.

6.2.2. Connectivity Facilities and Users' Health after COVID-19 Outbreak

On the other hand, connectivity facilities to the aboveground space, such as escalators, lifts, staircases, and so on, could serve to alleviate the sense of isolation and enhance one's feeling of safety by providing a means of escape from the underground environment [27,107]. This, to a certain extent, explains the reason why connectivity facilities are one of the significant environment factors predicting the physical and psychological health of underground users in both the pre- and post-outbreak period.

6.3. Changes in Underground Environment Factors Influencing Users' Health after COVID-19 Outbreak

The impacts of thermal comfort on users' physical and psychological health were significant only in the pre-outbreak period, but not in the post-outbreak period. It is well recognized that the social distancing requirements have reduced the density of space users in public areas [108]. This is echoed by the significantly shorter time spent underground by the survey respondents in the post-outbreak period (refer to Section 5.3). A low-density environment could mean a lowered indoor temperature caused by heat transferred from the human body to the environment. Furthermore, in order to lower the risks of COVID-19 transmission, ventilation in underground space is often increased in the post-outbreak period. This, to a certain extent, explains why the temperature and CO₂ levels of all underground sites were lower in the post-outbreak period in the field measurement study (refer to Section 5.7). Previous studies have indicated that building occupants' thermal comfort is highly related to air velocity [109], which can be influenced by many factors, such as ventilation setting and space design (e.g., connection space to the aboveground

space) in an underground environment [12]. Underground space users' thermal comfort has thus enhanced significantly in the post-outbreak period (refer to Section 5.3). However, the environmental factor is only one of the aspects determining one's thermal perception. During the pandemic period, visitors had to wear masks, protective head coverings and/or clothing, which may have affected their thermal resistance, thermal perception, and health [110]. For instance, even though an environment with a lower indoor temperature has a higher chance of causing the common cold in users [111], the protective clothing may have moderated its negative effects on individual health. Further research is required to investigate the potential moderating effect of protective masks and clothing on the influence of underground thermal conditions on users' health.

The impacts of greenery comfort on users' physical and psychological health were significant only in the pre-outbreak period, but not in the post-outbreak period. In fact, one of the functions of indoor greenery is to reduce the temperature and relative humidity, which further influences space users' thermal comfort [112]. However, under the significantly lowered occupancy density during the pandemic period, indoor thermal comfort has already been enhanced (i.e., lower indoor temperature and increased ventilation). This is believed to have lowered the importance of greenery to users' health.

The impact of wayfinding on users' health was significant only in the pre-outbreak period, but not in the post-outbreak period. Both occupancy density and visual access are critical to users' wayfinding in a built environment [113]. Under a high occupancy density, space users' visual access and exposure to different locations and exits are limited, which increases users' reliance on wayfinding systems, such as signage and site maps. However, after the pandemic outbreak, the occupancy density in underground sites has significantly lowered, which may have diminished the importance of wayfinding systems in the underground environment.

The impact of acoustic comfort on users' health was significant only in the pre-outbreak period, but not in the post-outbreak period. The field measurement study indicated that changes in the noise level across the underground sites were different (refer to Section 5.7). Even though ambient noise caused by humans may have been reduced due to the lowered occupancy density in the underground sites, there could be an increase in mechanical noise generated from HVAC systems (which is common in the pandemic period, since higher ventilation can minimize COVID-19 risks [114]). It is, however, interesting to note that the survey respondents had a higher satisfaction level towards acoustic comfort after the pandemic outbreak (refer to Section 5.3). In fact, individuals' visual and acoustic perceptions are interrelated [115]. The visual perception of quietness due to lower occupancy density may have affected underground space users' audio perception of noise level in the underground environment. In the post-outbreak outbreak period, visual factors may play an essential role in shaping space users' perception of an environment [116]. Further studies are recommended to investigate the interactions between the audio and visual perception of underground space users under different occupancy density levels.

Following the New Normal, the number of visitors to underground spaces may increase again. Future studies are recommended to investigate the potential changes of underground space user density on the associations between the underground environment and human health.

6.4. Evidence-Based Recommendations for Health-Centric Underground Environment Elements in the Post-Outbreak Era

The open-ended question results provided evidence for practical recommendations to foster a health-centric underground environment through toilet management, hygiene facilities, HVAC systems, personal hygiene monitoring, crowd management, hygiene education, and so on, in the post-COVID-19 era.

Toilet management was found to be the most-concerning issue (raised by more than 30% of respondents) amongst the underground space users who responded. Previous studies have indicated the significant impact of toilet hygiene on users' health status in the

COVID-19 period (e.g., fecal transmission of COVID-19 in developing countries [117]; gastrointestinal infections in post-disaster evacuation environments [118]). With Hong Kong being a metropolitan city, its toilet facilities are supposed to be comparatively advanced and hygienic. However, respondents complained that the toilets in their underground developments were smelly and dirty. The respondents expressed that, while toilets for visitors were relatively clean and tidy, the hygiene conditions of toilets for tenants/employees in the underground developments were poor, including odor, full trash bins, dirt, and so on. In addition to the toilet area, respondents also indicated that there was insufficient ventilation and fresh air supply in the queuing area outside the toilets. The implications here for underground environment and facilities management professionals include: (i) increasing toilet cleaning and sanitizing standards and frequency in general (since toilets were found to be the major concern of underground space users); (ii) extending good hygiene standards from visitors' toilets to tenants'/employees' toilets and the area outside toilets; (iii) review and increase, if needed, the number of toilets in underground developments so as to prevent crowds caused by queuing for toilets; (iv) providing automatic toilet doors so as to prevent COVID-19 transmission caused by touching virus-contaminated surfaces.

Secondly, the importance of hygiene facilities was raised by more than 20% of respondents. The pandemic has brought us to a new era where cleanliness has become paramount. The provision of hand sanitizers, disinfection products, and more garbage bins might just have been value-adding in the past, but these have now become necessary facilities for maintaining public health and safety. The transmission of COVID-19 has been reported to occur via droplets, fomites, airborne particles, and contact with contaminated surfaces. This poses a risk to cleaners who need to spend time in public areas to clean and disinfect, including high-touch surfaces. These risks are further increased in underground development areas that have inadequate ventilation, as reflected by the respondents (refer to Item 3 in Table 9). As such, the adoption of cleaning robots and/or automatic, touchless systems could enhance the health and safety not only of underground space users, but also underground cleaning staff, through effectively reducing human exposure to probable contamination routes (both respiratory and contact routes; e.g., [119]). In addition to minimizing environmental health risks, ensuring personal hygiene is another critical aspect of pandemic control. While personal hygiene education can play a role in pandemic control (through posters, broadcasts, mobile apps, etc.), the pandemic outbreak has also driven the development of various technologies that aid personal hygiene monitoring in public areas, such as intelligent face-mask and body-temperature-detection systems.

Echoing the findings of previous studies related to underground air quality (e.g., [12,28]), respondents complained about inadequate ventilation and high temperatures in underground developments, especially underground car parks, which are often ignored due to the short period of time users stay and the employees needed to staff it, who are in limited supply. Air pollution has been found to be a risk factor for COVID-19 infection since it carries microorganisms and affects the body's immunity [120]. It has been found that even short-term exposure to air pollution is significantly associated with COVID-19 infection [121]. As such, it is essential to review and upgrade the HVAC systems in underground development areas, including not just the main business areas, but also car parks and queuing areas outside toilets, so as to enhance air quality by increasing the air exchange rate. In addition, HVAC UV light disinfectant systems can also be installed for a continuous clean air supply for central air conditioning.

When compared with underground developments in other countries, underground developments in Hong Kong are relatively smaller in area, which causes challenges for tenants and users when it comes to maintaining a safe social distance, especially in developments with small shops located side by side. As such, some respondents commented that the underground development environment is too crowded, which may further cause health risks to users by increasing potential air (poor ventilation) and contact transmission. To control crowds, it is recommended that underground environment and facilities management professionals review the spatial configuration of their underground developments

(e.g., considering a linear spatial configuration that enables spatial segregation, clear and direct wayfinding, etc. [36]) and to manage users' behaviors through social distancing signage, monitoring apps, etc. (e.g., [122]). Furthermore, to enhance the effectiveness of crowd management, various innovative technologies can be deployed as suggested in the literature. For instance, wireless technologies (e.g., WiFi-enabled Internet of Things devices [123], scalable Bluetooth low-energy approach [124], RFID [125]), sensors (e.g., smartphone [126], sensor-fusion [127]), computer vision, and artificial-intelligence-enabled monitoring systems can provide real-time occupancy detection, tracking, and prediction for effective crowd control and wayfinding support. For instance, occupancy rates can be predicted using deep learning architectures based on various sensor data, such as indoor CO₂ levels and the number of WiFi-connected devices in different space types [127].

7. Research Implications

This study provided empirical support for the significant roles of connectivity facilities with aboveground spaces and visual comfort in fostering underground space users' physical and psychological health in the post-outbreak era. Underground space designers are recommended to enable sufficient connectivity facilities in an underground environment. Furthermore, it is important to enhance users' visual comfort in underground environments in the post-COVID-19 period. It is suggested that the ambient light level be increased (within the suggested range as indicated in guidelines or codes [128]), so as to allow one to have an overview of the environment, and adjust the light in garbage and waste management areas so as to enhance people's perception of cleanliness in the public space [49].

The questionnaire survey's findings go beyond the consciousness of underground space users and unveiled the objective impacts of connectivity facilities and visual comfort on respondents' self-perceived health level in the post-outbreak era. Although other underground environment factors, such as ventilation, IAQ, and anti-epidemic hardware and software, were found to be insignificant in the post-outbreak data, this does not mean that they are not important. Ensuring end-users' satisfaction is one of the key objectives of built environment management. The qualitative feedback collected in the open-ended question demonstrated that underground space users, based on their perception and cognition, put an emphasis on underground ventilation, IAQ, and anti-epidemic hardware and software when considering their health. Based on the results of both the quantitative questionnaire survey (Sections 5.4 and 5.5) and the qualitative open-ended question (Section 6.3), the recommended health-centric underground environment management approaches for the post-outbreak era results are summarized in Table 10.

Table 10. Recommended underground environment management approaches for users' health in the post-outbreak era.

Recommended Underground Environment Management Approaches		Evidence
Space management	Connectivity facilities	Quantitative survey (Table 7)
	- Physical (e.g., escalators, lifts, staircases, atriums)	
	- Virtual (e.g., virtual windows, ceilings)	
Building services	- Implicit (e.g., nature elements in design, furniture, fixtures)	
	Light management in main business and waste management areas:	
	- Light intensity	
	- Focus areas of light	

Table 10. Cont.

Supporting element	Recommended Underground Environment Management Approaches	Evidence
	Ventilation and IAQ management in: - Main business areas - Supporting areas (e.g., car park)	Qualitative open-ended question (Table 9)
	Anti-epidemic hardware: - Hygiene management in main business and supporting areas (including toilet, queuing areas): • Quality (service, standards, and innovative technologies such as automated systems, touchless facilities, and robotics) • Quantity (number of toilets)	
	Anti-epidemic software: - Personal hygiene monitoring • Intelligent face mask supervision, temperature checking - Crowd management • Spatial configuration, wayfinding system, social distancing signage	
	- Hygiene education through • Mobile apps, posters, broadcasts	

8. Conclusions

Due to the absence of sunlight, natural ventilation, isolation from the aboveground/natural environment, etc., underground space users are believed to face a higher level of health risks when compared with their aboveground counterparts, let alone the additional risks brought by the outbreak of COVID-19. However, it is interesting to find in this study that, when compared with the pre-outbreak period, the physical and psychological health of underground space users were significantly better after the outbreak. This can be explained by the increased time available for individuals to take care of their health as a result of the slower living pace due to the pandemic. More importantly, underground users' satisfaction with various underground environment elements was enhanced after the outbreak. This, to certain extent, indicated that the pandemic has brought positive impacts to the underground environment profession by driving its performance through government policies, market pull, and technology push.

On the other hand, the study provided empirical support that the impacts of the underground environment factors on users' health have changed after the pandemic outbreak. The expectations of underground users about different underground environment elements have also changed. With the increasing need to develop healthy underground spaces, the research in this paper contributes to underground development design and management (from the comprehensive perspectives of space management, building services, and supporting elements) to foster users' physical and psychological health.

This study's results highlighted the significant roles of connectivity facilities with the aboveground space in fostering underground space users' physical and psychological health in the post-outbreak era. Once a development is completed, it is difficult or costly to change its hardware connectivity facilities, such as escalators, lifts, staircases, etc. Other approaches to create connections between underground and aboveground environments can be virtual (e.g., virtual windows or ceilings displaying aboveground or natural environment) and implicit (e.g., embedding aboveground or nature elements in the underground interior design, furniture, and/or fixtures) connectivity facilities [129,130]. Further studies are recommended to investigate the connectivity options comprehensively and systematically.

The survey study adopted a self-report measurement approach, which could have resulted in common method variance. Furthermore, the sample may be prone to non-response and social desirability bias. However, it should be noted that the data collection was purposively designed to include respondents with diverse backgrounds (in terms of age, gender, health behaviors, and health history) and cover underground developments of different ages, types, location, and design. On the other hand, it is acknowledged that a within-subject design (i.e., the same group of respondents in both pre- and post-outbreak periods) can reduce potential errors caused by individual differences. However, since a within-subject design may cause difficulties in respondent recruitment and the results may also be affected by a carryover effect [131], the study adopted a between-subject design, in which respondents participating in the pre- and post-outbreak periods were different. To minimize the potential effects of individual differences on the research findings, two measures were adopted. Firstly, both sample groups were formed from the same pools of underground sites, and they had mixed demographic backgrounds in terms of age, gender, and occupation. Secondly, personal background factors, such as age, gender, smoking habit, chronic illness, long-term medication, and time spent underground, were all controlled for in the multiple regression analyses and SEM. Meanwhile, to minimize the possibility of social blowback, an anonymous questionnaire survey was adopted in this study. Before filling in the survey, each respondent was assured about data confidentiality and that no personal identifiers would be recorded. The measurement scales in this study were adopted from the extensive literature on built environments and post-occupancy evaluations.

With the aims to investigate the impacts of the general underground environment on the health of regular users and to extend the universal built environment–QoL model to underground spaces, the study adopted a mixed underground space approach, i.e., collecting data from common underground environments, including subways, shopping centers, and offices, and analyzing them in an integrative way. This approach has been widely adopted by previous underground space studies with comparable research aims, e.g., [132,133]. It is acknowledged that, different from regular users (i.e., employees), irregular users such as passengers and customers conduct different activities in different space types, e.g., transiting in subway stations and shopping in shopping centers, and this may result in a difference in their health levels. To further examine the impacts of different underground space types on the health of these irregular, short-staying users, future studies are recommended to develop and compare underground environment–health models for users of different underground space types.

The R^2 value indicates the amount of model variance that can be explained by the corresponding regression model [134]. In this study, the R^2 values of the multiple regression models ranged from 0.189 to 0.537. Even though the values were comparable with some other health-related studies, this indicated that the explanatory power of the regression models was limited, especially in the post-outbreak period. It is postulated that, in addition to the underground environmental factors and the controlled variables, there can be other factors that influenced participants' health, such as individual's health behaviors, exercise habits, food intake, and so on. These factors may have also been changed by the pandemic. While this study, to a certain extent, provided empirical support to the significant relationships between the underground environment and users' health, further studies are recommended to investigate in-depth the effects of other health-related behavioral factors on the relationships between the underground environment and users' health in the post-pandemic era.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Health measurement.

Measurement Items for Health (Pre- and Post-Outbreak)		References
<i>Physical health</i>		
1.	Dry eye	[33,70]
2.	Itchy or watery eyes	
3.	Blocked or stuffy nose	
4.	Runny nose	
5.	Dry throat	
6.	Lethargy or tiredness	
7.	Headaches	
8.	Dry, itching or irritated skin	
9.	Sneezing	
10.	Breathing Difficulties	
11.	Insomnia	
<i>Psychological health</i>		
1.	I feel emotionally drained by my work	[69,135]
2.	I feel used up at the end of the workday	
3.	I feel fatigued when I have to get up in the morning to face another day on the job	
4.	I feel “burned out” from my work	
5.	I worry that this job is hardening me emotionally	
6.	I feel frustrated by my job	
7.	I feel I’m working too hard on my job	
8.	I feel like I’m at the end of my rope	

Table A2. Underground environment satisfaction.

Measurement Items for Underground Environment (Pre- and Post-Outbreak)		References
1.	How satisfied are you with the number of natural landscape elements in this underground work environment? eg. plants, wood, stone, water, images of outdoor etc.	[107,136,137]
2.	What do you think about the easiness of the immediate access to aboveground?	
3.	How satisfied are you with the wayfinding support in this underground work environment?	

Table A2. Cont.

Measurement Items for Underground Environment (Pre- and Post-Outbreak)		References
4.	How satisfied are you with the thermal comfort in this underground work environment?	[107,136,137]
5.	How satisfied are you with the ventilation in the underground work environment?	
6.	How satisfied are you with the air quality in the underground work environment (i.e., stuffy/stale air, cleanliness, odours)?	
7.	How satisfied are you with the noise level in the underground work environment?	
8.	How satisfied are you with the visual comfort of the light in the underground work environment?	

Table A3. Anti-epidemic hardware and software satisfaction.

Measurement Items for Anti-Epidemic Hardware and Software (Post-Outbreak)		References
1.	How satisfied with the overall hygiene and cleanliness in the underground environment?	[138,139]
2.	How satisfied are you with the temperature checking at entrance of the underground environment?	
3.	How satisfied are you with the temperature checking in common areas of the underground environment?	
4.	How satisfied are you with the temperature checking in office/shop in the underground environment?	
5.	How satisfied are you with the hand sanitizer at entrance in the underground environment?	
6.	How satisfied are you with the hand sanitizer in common areas in the underground environment?	
7.	How satisfied are you with the hand sanitizer in office/shop in the underground environment?	
8.	How satisfied are you with the public education or promotion on hygienic practices in the underground environment (e.g., signage, posters)?	
9.	How satisfied with the overall disinfection products in the underground environment (e.g., handrail sterilizer on escalator, touchless button in lift, touchless mask disposal bin, automatic-entrance door)?	
10.	How satisfied are you with the crowd control in the underground environment?	

Open question

How can facilities management be enhanced to lower underground occupant's health risks under COVID-19?

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