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The importance of Air Quality for Underground Spaces:
an international survey of public attitudes

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Abstract

Space is a resource that is constantly being depleted, especially in mega-cities. Underground workspaces (UGS) are increasingly being included in urban plans and have emerged as an essential component of vertical cities. While progress had been made on the engineering aspects associated with the development of high-quality UGS, public attitudes towards UGS as work environments (i.e. the public's design concerns with UGS) are relatively unknown. Here, we present the first large-scale study examining preferences and attitudes towards UGS, surveying close to 2,000 participants from four cities in three continents (Singapore, Shanghai, London and Montreal). Contrary to previous beliefs, air quality (and not lack of windows) is the major concern of prospective occupants. Windows, temperature and lighting emerged as additional important building performance aspects for UGS. Early adopters (i.e. individuals more willing to accept UGS and thus more likely to be the first occupants) across all cities prioritised air quality. Present results suggest that (perceived) air quality is a key building performance aspect for UGS that needs to be communicated to prospective occupants as this will improve their attitudes and views towards UGS. This study highlights the importance of indoor air quality for the public.

Practical Implications

This study gives a clear message regarding the public significance of air quality: it establishes the importance of air quality as a key architectural or engineering concern for underground spaces (UGS). Thus, engineers, policymakers and researchers can employ findings of this study as a justification to invest and research on improving air quality. Insights of this study could be used to build and/or design more desirable UGS, thus increasing adoption of such workspaces.

Keywords: Underground workspace, attitudes, building performance aspects, air quality, windows, indoor space

1. Introduction

Space is a natural resource that, while dwindling, is much less appreciated and examined than other resources such as air, water and energy. In particular, space depletion is a major source of significant problems that cities now face. With ever-increasing population density in urban areas, the vertical development of cities and mega-cities seem to be a viable, if not inevitable, solution.[1] Though high-rise buildings can help towards the sustainable development of modern over-populated cities, policymakers have been exploring and, in many cities, actively adopting further usage of underground spaces. (Notice that here, the term ‘underground workspaces’ does not refer to deep underground spaces or mines, but rather to regular workspaces such as offices, storage, data centres, and malls that can typically be found in cities). Indeed, boosted by rapid technological developments in engineering, numerous underground workspaces (UGS) oriented for humans have been (or are planned to be) built in many cities across the world.[2,3] Major examples include Montreal, Shanghai, London, Oslo, Stockholm, Tokyo, Dubai, Seoul, New York and Singapore – thus it is a solution that concerns tens of millions of people. Moreover, futuristic projections talk about depth-scrapers and earth-scrapers, a technologically viable solution.[4]

UGS offer many advantages,[5] including better protection from extreme weather, lower commute time (as they increase the space available to business districts), better control of climatic conditions (air quality and temperature) and increased fire safety and protection from natural disasters. UGS can reduce the horizontal expansion of urban regions allowing for more space for nature parks and croplands and gas emissions.[6,7] UGS have additional advantages compared to upwards vertical development, as they free up space for nature and can protect culture and heritage, especially in older cities such as Athens or Rome, where high-rise buildings will obscure the cultural landscape.

During the last decade, civil engineering has made significant progress in the construction of UGS. In fact, from an engineering point of view, UGS could share most of the characteristics of similar aboveground indoor spaces. Technically, there are no substantial differences between conventional aboveground offices and underground offices with similar settings, except for the lack of windows facing the outside world.

It is now time to examine the largely unanswered questions of how the public reacts to the idea of working in UGS and the major concerns and preferences for these spaces. Some research in the 1980s and 1990s sporadically discussed the importance of these issues (for a recent review see [8]), but since then there has been a lack of systematic and large-scale research on how the public responds to UGS.[9] Moreover, social scientists have rarely been involved in this research to bring in robust attitudinal methods of scientific enquiry. However, UGS are still not a mainstream solution. As with any innovation, successful adoption depends not only on the current technological capacities but also on public beliefs about the prospect of working in such an environment. As such, understanding attitudes towards UGS is urgent. An analytical understanding of these attitudes will help city planners, urban developers, policymakers and architects ensure that the precious resource of space in mega-cities will not be wasted due to a lack of human-centric development that respects expectations, needs and preferences, while reducing any biases,[10] especially against the very concept of underground development.

Earlier and small-scale studies suggested that people often associated underground with stuffiness and dampness[11] and, therefore, tended to evaluate UGS as undesirable. However, negative attitudes to UGS could be driven by unfounded, outdated underlying beliefs or overreactions, rather than by actual effects, especially given recent technological advancements.[12] For example, UGS could be advantageous in terms of earthquake protection compared to aboveground facilities, but the public tends to hold the opposite belief.[13] In case of an earthquake, over 50% of respondents in one study said they would evacuate from an underground train station to ground level, compared to 5% who would stay.[14]

Attitudes overall, and preferences over environmental and design parameters in particular, vary from person to person. Here, following de Wilde[15], we use the term "building performance aspects" to describe key aspects of the UGS (such as temperature, air quality, lighting, lack of windows, humidity, noise level, privacy – the full list is presented at section 2.3). Previous research has shown that satisfaction with such building performance aspects determines how occupants perceive the environment and affects their (human) performance[11,16–23] A well-designed office reduces mental stress and improves productivity.[24–27] Many common features should be considered when designing a workspace. For instance, windows are favoured by most office workers, possibly due to the fresh air, better views, natural daylight and psychological comfort they are associated with.[28] The air quality of a room can influence work performance too. Poor air quality and lower rates of ventilation were associated with higher number of sick leave days taken by workers.[29] Better air quality and ventilation rates were associated with better work performance and health (fewer Sick Building Syndrome [SBS] symptoms).[30] Noise and poor acoustics may impact performance and therefore need to be minimised to ensure acoustic comfort.[16] Lack of privacy has been associated with lower levels of concentration, higher stress and compromised performance.[31–34] Therefore, providing a comfortable work environment that caters to the needs of occupants – i.e. human-centred design – has attracted the attention of many researchers and developers (for instance, the LEED certification;[35]) over recent decades. Importantly, occupants themselves implicitly or explicitly weigh these performance aspects when considering working in or moving to such an office space.[36,37]

For such a novel question, it is important to start from the basics, but also to get data from different cities to ensure that results apply to many different environments. Few studies have examined the architectural, design and functional features of a space ("building performance aspects”)[38] that prospective occupants perceive as important for underground spaces. The present study aims to enrich our understanding of attitudes towards UGS by answering the following basic questions: (1) Which performance aspects (such as air quality, lighting, noise, evacuation) are prioritised for a UGS overall? (2) Do preferences for performance aspects change as a function of the extent to which somebody is more (‘early adopters’) or less (‘late majority’) willing to work in UGS? The present study aims to formally answer the long-standing question of where architects should focus to improve the public perception of UGS (and possibly by extension to indoor aboveground windowless spaces) and ensure occupant comfort, at least in terms of expectations.

These questions were examined by employing a large-scale, systematic, multi-city questionnaire that elicited responses from a wide range of people in four different major cities in four countries and three continents. Note that in our study we do not discuss UGS as either a form of social dilemma or a shared public good – we do not emphasise the overall positive environmental aspects of UGS for cities and the environment. Rather, the choice to adopt a UGS is presented as a personal choice isolated from any societal benefits.[39]

2. Materials and methods

2.1. Study population and design

2.1.1. *Study Design*

This was a cross-sectional study. The study was conducted entirely online, where participants received and completed a series of online questionnaires. Apart from Shanghai, questionnaires distributed were in English. Participants from Singapore, London and Montreal were recruited if they indicated that they could understand and use English with few to no difficulties. For Shanghai, the questionnaire distributed was in Simplified Chinese. The questionnaire was translated from English to Chinese and then back-translated to ensure accuracy; contentious items were resolved by bilingual reviewers.

Participants recruited from Singapore were either citizens or permanent residents while participants from the other three cities lived in the respective cities for at least ten years.

2.1.2. *Cities*

Some notes about the choice of cities (Singapore, Shanghai, London and Montreal) are essential. Firstly, the four cities were selected with the primary criterion of having already adopted underground spaces, each for various reasons. For example, in these cities, many shopping malls, public transportation systems or places of entertainment (such as theatres and restaurants) are located partially or fully underground. In addition, the cities have a variety of climate conditions: tropical (humid, equatorial) rainforest in Singapore; temperate oceanic climate in London; humid subtropical climate with hot summers in Shanghai; and warm summer continental climate (with snowy winters and warm summers in Montreal).[40] Finally, they represent different cultural backgrounds and are major economic centres oriented towards services, therefore trending towards the need for office space instead of factories. In the future, other cities should be examined: for instance, Rome, Athens, or Mexico City might need UGS in order to protect their cultural heritage or to deal with significant infrastructure issues.

2.2. Data collection

Data collection was independently conducted by a professional research company (Qualtrics) using panels of respondents – this method and, in fact, the specific research panel follows high industry benchmarks (such as the European Society for Opinion and Market Research) and research standards and has thus been widely used by many researchers in the social sciences as well as many major private companies.[41–43]

In order to gain a better understanding of the general public's attitudes and preferences towards UGS and workspaces, we took special care to ensure that the majority of participants recruited were working adults as these individuals should have more experience with workspaces in general. Exclusion criteria were age (being younger than 21), not being resident of the specific city and English language ability (except Shanghai). There were no participant-specific inclusion criteria, but there were sample-level inclusion criteria, i.e. the sample was adjusted to approach equal representation of men and women, an at least 50% representation of ages 31-50 (given this is the most active part of the population), to be employed (over 90% employed, at least 60% having a desk-bound type of work).

Data collection was conducted during different time periods for each city. Data collection was conducted from June 2016 to February 2017 for Singapore, September 2018 to October 2018 for London, November 2018 for Shanghai and November 2018 to December 2018 for Montreal.

2.3. Questionnaire measures

Participants' basic demographics information (gender, age, education level, ethnicity, marital status, etc.) and their past underground work experience were reported. The other variables of interest are described as follows.

Attitudes towards UGS. The Underground Workspaces Questionnaire (UWSQ) is a validated 16-item scale that measures general attitudes towards underground environments.[44] All items were answered on a seven-point Likert scale (1 = strongly disagree to 7 = strongly agree). The attitudes questionnaire includes three subscales: positive attitude, negative affect and negative cognition. The score for each subscale is calculated by summing the scores of relevant individual items. Higher scores in positive or negative subscales reflect a greater tendency in that dimension. The general score was obtained by adding the scores of all subscales based on their valence and was then mean centred. A higher value of a general score indicates a more favourable general attitude toward UGS.

Willingness to work underground. This is a typical scenario-based question where participants were instructed to assume that they had applied for a new job which required them to do the same type of work as their current job, with the difference that the office of the new company was located on a basement level eight. Participants rated the likelihood of accepting the job offer on a seven-point Likert scale from extremely unlikely (1) to extremely likely (7).

Critical features of underground offices (*architectural parameters)*. After an extensive literature review and interviewing of experts and users of UGS (described in[5,8,45,46]), we generated 12 building performance aspects that could be motivators of the negative associations of underground workspaces. The final list of concerns is listed in Figure 1. For instance, given that underground offices are often windowless due to geological factors,[47,48] we listed 'lack of windows' as a potential concern for prospective users. Perceived safety (e.g. ability to evacuate from an interior fire or explosion because of limited access to the ground level) is associated with willingness to work underground and turnover rates,[13] and may thus influence attitudes. Another important contributor is lighting. Due to the absence of natural daylight in UGS, lighting could affect workers' productivity, psychological comfort and sleep.[49] Communication and interaction (within the underground workplace, between surface networks and perceived distance from above ground) also influence experience in UGS, as Wi-Fi connections and mobile signals may operate less effectively than in aboveground offices, leading to feelings of isolation and confinement.[50]

Participants were instructed to assume that their office was located at a deep basement level (i.e. basement level eight [B8]). They were then asked to order the list of building performance aspects by the extent to which they would be concerned or worried about them, from most to least concerning. To clarify, the list was presented to the participants as a menu and the participants could select each item and drop it above/below the other items in the list to indicate the rating. These building performance aspects were temperature, air quality, lighting, lack of windows, humidity, noise level, privacy, amount of space, interaction with people in other workspaces, mobile signal quality, unawareness of events outside (e.g. weather), and evacuation.

2.4. Statistical analysis

2.4.1. *Data screening*

The original sample consisted of 1093, 313, 315 and 409 residents from four cities, Singapore, London, Shanghai, and Montreal respectively. Participants who did not complete the whole questionnaire were excluded from analyses. In addition, we added a ‘catch’ question estimating the depth of basement level eight in metres to screen for careless respondents. Those with extremely unrealistic estimations were filtered out. Hence, there were N=983, N=289, N=312 and N=388 participants remaining, for Singapore, London, Shanghai, and Montreal respectively, for data analysis.

2.4.2. *Data analysis*

We first explored the relationship between intended behaviour and attitudes – a central aspect of attitudinal research that needs to be examined early on.[51] We used spearman’s rank-order correlation (two-tailed), to examine the likelihood of individuals accepting a job offer at UGS and their attitudes towards UGS, where *p*-values of < 0.05 were considered to be statistically significant.

In order to better understand or identify differences between rankings of features for an UGS across the cities, we employed R-index analysis, a technique widely used in ranking data to define the probability of selecting one stimulus or product over others.[52] R-index analysis is ideal as it offers a measure of spacing between the different architectural parameters in underground offices.[52] The values of R-index indicate varying degrees of preference. R-indices were calculated in a pairwise fashion between adjacent features based on descending mean. A value of R=50% indicates that there is no overall preference between features compared, whereas a value of R=100% suggests that all participants felt that the reference feature was more important than the feature compared. The critical value of significance at 0.05 level (two-tailed) for Singapore, London, Shanghai and Montreal were R=52.59%; R=54.76%; R=54.52% and R=54.09% respectively.[53,54] An R-index at or above the critical value suggests that the reference feature is significantly more likely than random chance to be perceived as more important than the adjacent feature.

The last critical question is whether participants who are more ('early adopters') or less willing ('late majority') to work underground have particular preferences or concerns for certain building performance aspects. As for any innovation, one could target the early adopters before expanding to the whole population – a strategy that has been proven to be effective.[55–57] Concurrently, if the target space is oriented to any kind of occupants, then the focus could be on the part of the population that is more likely to raise concerns.

To answer this, participants were categorised into two groups (low and high willingness to work in an underground office) using the median split, before conducting another R-index analysis for the two groups separately. The critical values of significance at 0.05 level (two-tailed) were R=54.45% and R=53.13% for the low- and high-willingness groups respectively for Singapore, R=57.22% and R=56.27% for the low- and high-willingness groups respectively for London, R=56.47% for both groups for Shanghai, and R=56.70% and 55.14% for the low- and high-willingness groups respectively for Montreal.[53,54]

2.5. Ethics approval and data availability

The study was approved by the Institutional Review Board of Nanyang Technology University (NTU) (IRB-2015-06-031). Online informed consent was obtained from all participants prior to commencement of data collection.

The data that support the findings of this study are available from the corresponding author upon reasonable request.

3. Results

The original sample consisted of residents from four major cities (Singapore, London, Shanghai and Montreal): 1,093 Singaporean citizens and permanent residents (71.6% Chinese. 14.9% Malay, 10.2% Indian and 3.2% others); 313 individuals who lived in London for 10 years or longer (71.6% White, 13.1% Black or Afro Caribbean/African, 6.4% South Asian, 3.2% East Asian, 0.6% Middle Eastern, 4.5% others and 0.6% not specified); 315 individuals who lived in Shanghai for 10 years or longer (98.7% Han Chinese, 0.6% Zhuang people and 0.6% Hui people); and 409 individuals who lived in Montreal for 10 years or longer (76.3% White, 5.6% Black or Afro Caribbean/African, 4.4% South Asian, 9.3% East Asian, 0.7% Middle Eastern, 0.5% First Nations and 3.2% others). Table 1 presents demographics of participants in all four cities, including age, type of work and highest level of education.

Table 1. Cross-tabulation of demographic information for all cities

	Singapore		London		Shanghai		Montreal	
	N	%	N	%	N	%	N	%
Gender								
Male	499	50.8%	144	49.8%	169	54.2%	192	49.5%
Female	484	49.2%	145	50.2%	143	45.8%	196	50.5%
Total	983	100%	289	100%	312	100%	388	100%
Age								
30 or under	258	26.2%	33	11.4%	159	51.0%	73	18.8%
31–50	555	56.5%	162	56.1%	150	48.1%	230	59.3%
Over 50	170	17.3%	94	32.5%	3	1.0%	85	21.9%
Total	983	100%	289	100%	312	100%	388	100%
Education								
Secondary or under	160	16.3%	84	29.1%	5	1.6%	140	36.1%
Diploma	246	25.0%	162	56.1%	17	5.4%	186	47.9%
University level or above	577	58.7%	43	14.9%	290	92.9%	62	16.0%
Total	983	100%	289	100%	312	100%	388	100%
Type of work								
Desk-bound	628	63.9%	217	75.1%	242	77.6%	296	76.3%
Requires movement	314	31.9%	54	18.7%	67	21.5%	76	19.6%
Others	40	4.1%	18	6.2%	3	1.0%	16	4.1%
Total	982	99.90%[1]	289	100%	312	100%	388	100%

[1] 1 participant did not report their type of work.

3.1. Attitudes towards underground spaces

Results are presented for Singapore, London, Shanghai and Montreal respectively. Consistently across all four cities, participants who held more favourable general attitudes towards UGS were more likely to accept the job offer ($r_{Sing} = 0.63$, $r_{Lond} = 0.62$, $r_{Shan} = 0.69$, $r_{Mont} = 0.52$, all $p < 0.001$; r refers to spearman's rank-order correlation). Similarly, at the subscale level, higher positive attitudes were associated with a greater likelihood to accept the job offer ($r_{Sing} = 0.55$, $r_{Lon} = 0.63$, $r_{Shan} = 0.66$, $r_{Mont} = 0.50$, all $p < 0.001$), while higher negative attitudes were associated with a lower likelihood ($r_{Sing} = -0.52$, $r_{Lond} = -0.42$, $r_{Shan} = -0.55$, $r_{Mont} = -0.42$, all $p < 0.001$). These results suggest that attitudes towards UGS can influence the individual's intention to adopt underground spaces.

3.2. Critical features (building performance aspects) of underground workspaces

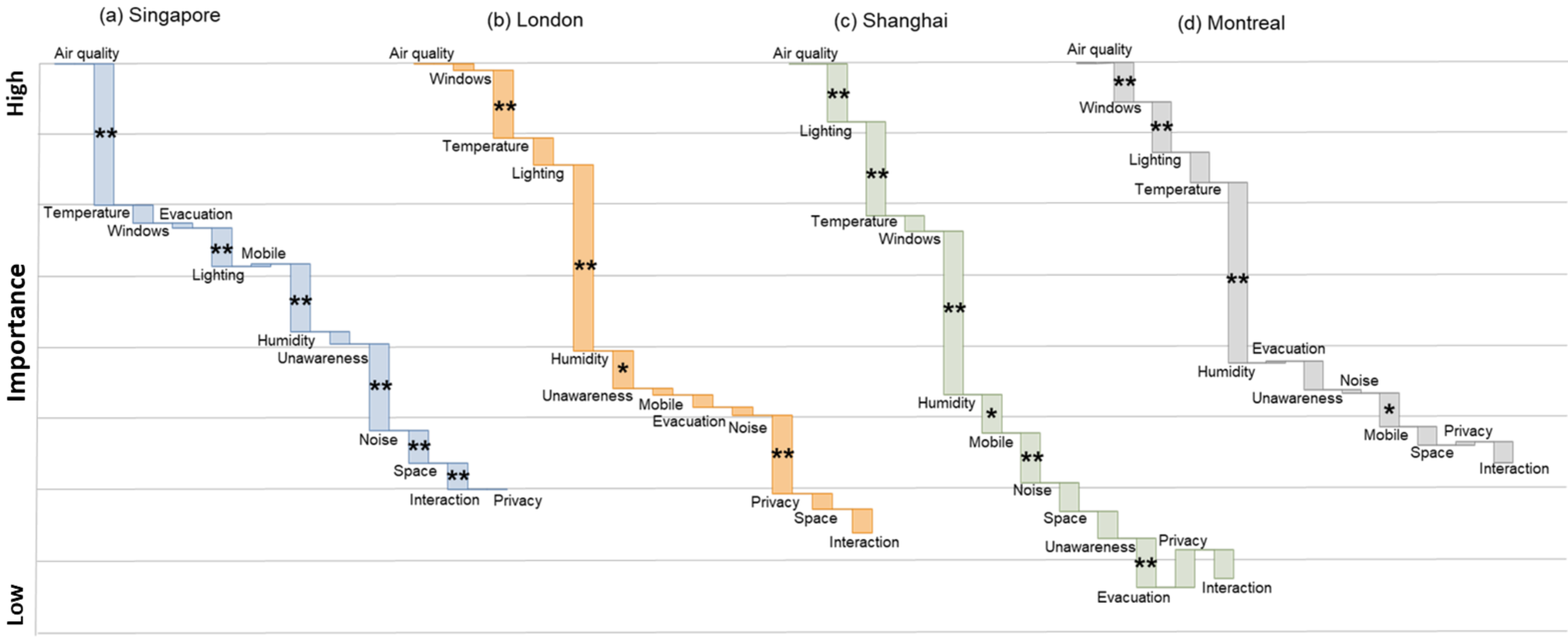
Figure 1 reports how participants from the four cities ranked different building performance aspects in an UGS by overall perceived importance (where higher values indicating greater perceived importance) for the four cities (mean-based analysis presented in Supplementary Table 1). The top four parameters were similar across the four cities, with air quality being the clear major concern in all cities, followed by temperature, lack of windows and evacuation for Singapore; lack of windows, temperature and lighting for London; lighting, temperature and lack of windows for Shanghai; and lack of windows, lighting and temperature for Montreal.

R-index results for Singapore participants are displayed in Figure 1a (complete results presented in Supplementary Table 2). Crucial building performance aspects were air quality followed by temperature (69.90%, $p < 0.01$), lack of windows (52.50%, $p > 0.05$), evacuation (50.73%, $p > 0.05$) and lighting (55.39%, $p < 0.01$). The figures with the results are more informative as they also indicate the degree of difference between the attributes (indicated by the length of the bars). Yet to further explain this and subsequent results: the p-values indicate significance as compared to the immediately following feature. Thus, for instance the results presented just above, mean that air quality is perceived as more important than temperature (and this is statistically significant); temperature is not (statistically speaking) different from windows and evacuation; and evacuation is more important than lighting (and so on).

For London participants (Figure 1b, full results presented in Supplementary Table 2), crucial building performance aspects of UGS were air quality and lack of windows (50.98%, $p > 0.05$), followed by temperature (59.56%, $p < 0.01$), lighting (53.73%, $p > 0.05$) and humidity (76.15%, $p < 0.01$).

As shown in Figure 1c (complete results presented in Supplementary Table 2), for Shanghai participants, crucial building performance aspects were air quality, followed by lighting (58.20%, $p < 0.01$), temperature (63.21%, $p < 0.01$), lack of windows (52.22%, $p > 0.05$) and humidity (72.85%, $p < 0.01$).

Lastly, for Montreal participants (Figure 1d, full results presented in Supplementary Table 2), crucial building performance aspects were air quality followed by lack of windows (55.40%, $p < 0.01$), lighting (56.90%, $p < 0.01$), temperature (54.06%, $p > 0.05$) and humidity (74.75%, $p < 0.01$).



*p < 0.05, **p < 0.01.

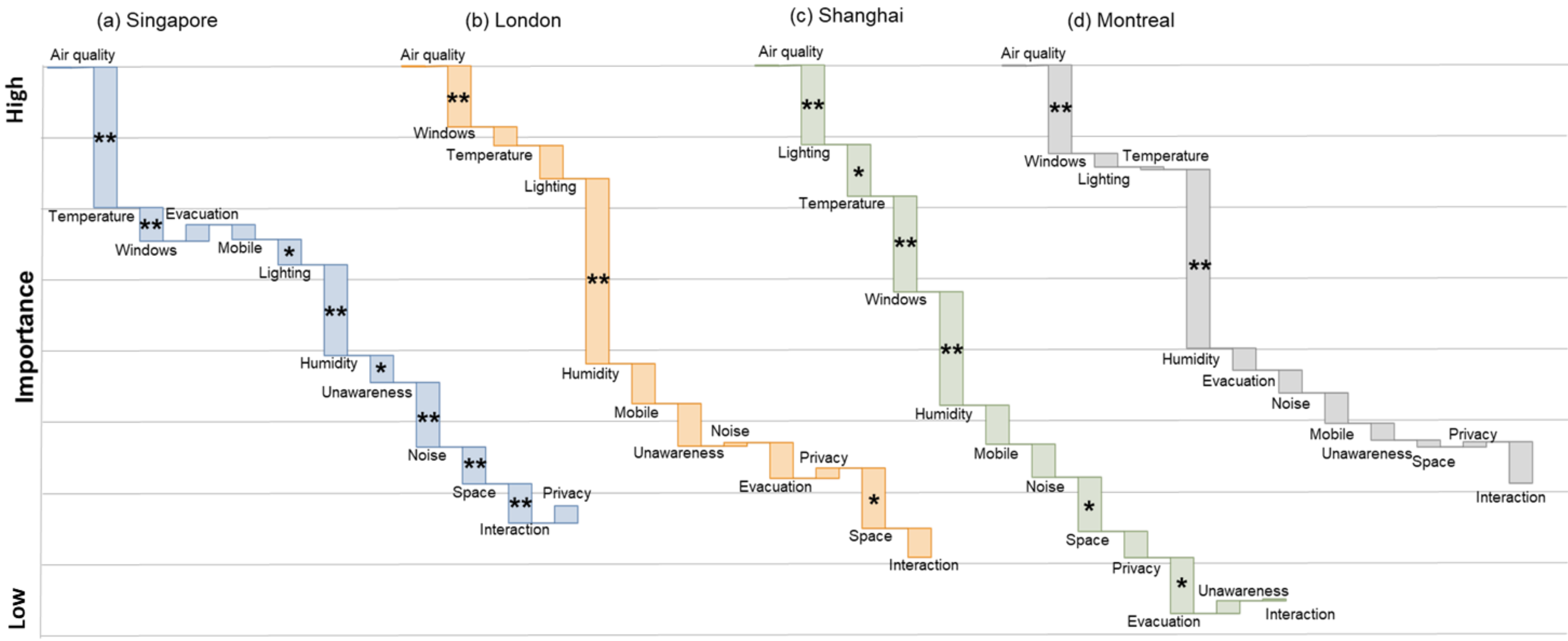
Windows, Lack of windows; Mobile, Mobile phone signal quality; Unawareness, Unawareness of events outside; Noise, Noise level; Space, Amount of space; Interaction, Interaction with people in other workspaces.

Figure. 1. Rank order of building performance aspects (from most to least concerning) in underground environments for all cities. The length of each bar represents the extent to which the reference variable was preferred over the adjacent feature (R-index - 50); thus, bars are not accumulative.

3.3. Willingness to work in an underground space

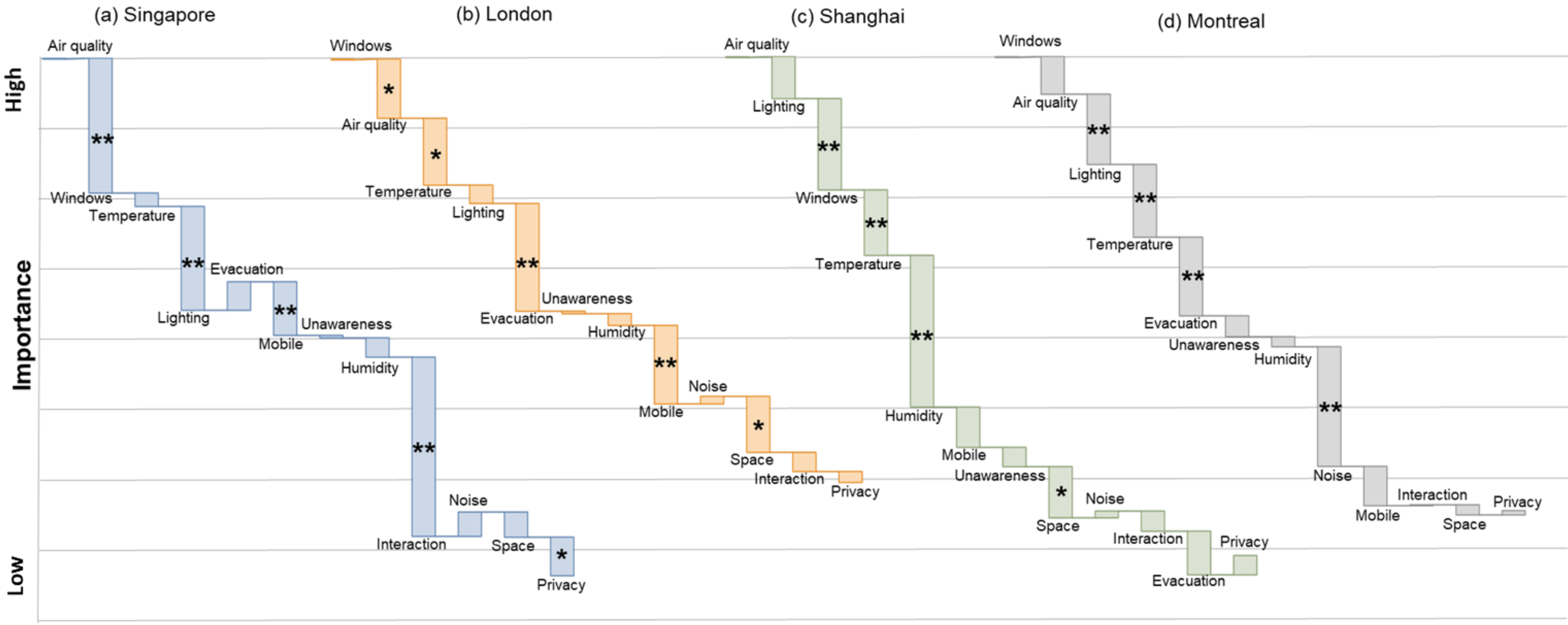
After categorizing the participants into two groups (early adopters and late majority), we examined the rankings of the building performance aspects of the two groups and four cities. In general, the top four important features (air quality, lack of windows, temperature, and lighting) remained the same, but the ranking within each city and each group differed. The only exception was for Singapore’s high-willingness group, where the four most important building performance aspects were air quality, temperature, lack of windows and evacuation.

R-index analysis was again used to gain a better understanding of the ranking differences. Figures 2 and 3 (mean-based analysis results reported in Supplementary Table 3) show the ranking of building performance aspects using R-index analysis, by overall perceived importance (where higher values indicate greater perceived importance) for the two groups for all cities (full results per city reported in Supplementary Tables 4-7). Results remain essentially the same in terms of ranking and importance for air quality, lack of windows, temperature and lighting. (For full results see Supplementary Tables 4-7).



*p < .05, **p < .01
Meaning of labels: Windows: Lack of windows; Mobile: Mobile phone signal quality; Unawareness: Unawareness of events outside; Noise: Noise level; Space: Amount of space; Interaction: Interaction with people in other workspaces.

*Figure. 2. Preferences for **"early adopters"**: Rank order of building performance aspects (from most to least concerning) in underground environment for the group with high willingness to work in an underground office for all cities. The length of each bar represents the extent to which the reference variable was preferred over the adjacent feature (R-index - 50); thus, bars are not accumulative.*



*p < .05, **p < .01
Meaning of labels: Windows: Lack of windows; Mobile: Mobile phone signal quality; Unawareness: Unawareness of events outside; Noise: Noise level; Space: Amount of space; Interaction: Interaction with people in other workspaces.

*Figure. 3. Preferences for **"late majority"**: Rank order of building performance aspects (from most to least concerning) in underground environment for the group with low willingness to work in an underground office for all cities. The length of each bar represents the extent to which the reference variable was preferred over the adjacent feature (R-index - 50); thus, bars are not accumulative.*

Yet, some more specific results are worthwhile to be highlighted. For all “early adopters”, air quality is, by far, the major concern. For London, Montreal and Shanghai, windows, temperature and lighting are prioritised as the next more important topics. However, Singapore is the only city that brings up evacuation as an important factor, even higher than lighting. This is interesting, as, for all other cities, evacuation is considered a very low priority for early adopters. On the other hand, “late majority” respondents showed more diversity. Air quality retained the first position for Singapore and Shanghai, suggesting that for these cities an investment in this aspect will pay out both short and long term; however, London and Montreal residents prioritised windows as their major concern, indicating that architectural aspects should be taken into account for these cities. In any case, air quality, windows, temperature and lighting remained as the major concerns for all four cities, in various ordering.

4. Discussion

The present study is the first to systematically investigate important factors associated with public concerns towards working in UGS (i.e. underground workspaces) using a large, diverse sample of the adult populations from several cities. For this relatively new issue, we first examined attitudinal aspects, followed by the critical features (building performance aspects) for a UGS. Air quality, lack of windows, temperature, lighting and ease of evacuation emerged as building performance aspects of concern for potential occupants when considering working in a deep underground office (basement level eight). Notice that the way the term “underground” is operationalised here is distinct from “working in basement” scenarios, where, while the working space is formally underground (i.e. below the surface of the earth and with no direct access to outdoor open spaces[8,58], it nevertheless could be confused with a space that is a mere extension of aboveground spaces. These elements have been informally speculated as important (for instance, there is significant literature on evacuation on underground spaces), but our data offer evidence that indeed the public is concerned with these elements, highlighting the need for developers and researchers alike to substantially consider them. Interestingly, with the exception of lack of windows, the other parameters (air quality, temperature, lighting, evacuation) not only can be solved by modern engineering, but could be substantially *better* in UGS compared to typical aboveground offices. For instance, evacuation in case of fire might be easier in an UGS compared to an office located on the 30th floor of a skyscraper. Similarly, air quality, temperature and lighting are much more (or just as) easily regulated in UGS.

Intended behaviour is a central aspect of attitudes towards an object. Thus, as a general validation exercise and to reflect typical attitudinal research in other domains, we investigated how attitudes influence intended behaviour by examining the relationship between attitudes towards UGS and possibilities of accepting a job offer where the office is located underground. Again, this question is theoretically important, as previous extensive research in social psychology has demonstrated that attitudes towards an object affect intended behaviour,[51] and this needed to also be validated for the UGS domain. Indeed, in all four cities, the relationship between attitudes towards working in an underground office was significantly and consistently correlated with intention to work in an underground office.

Subsequently, we examined whether any crucial building performance aspects were related to an individual’s willingness to work in an underground environment. Once again, air quality was the most important feature for participants who were more willing to work in an underground environment (early adopters) across all cities, and some participants who were less willing to work in an underground environment (late majorities). Thus, addressing the air quality issue will be adequate to resolve the major concerns of a significant part of the population.

Our study offers evidence that, contrary to anecdotal beliefs, public policy concerns and even some previous research – air quality is the most important concern, over and above other previously hypothesised parameters, including windows, wayfinding or lighting.[14,58,59] This is critical, from a practical point of view, as it redirects the construction priorities for UGS and can be used to promote user-centered design for underground spaces.[60]

Generally, better air quality could be achieved by improving ventilation rates or by installing additional or higher rated air filters. Previous studies[61,62] showed that by improving air quality of a room or by increasing ventilation rates, participants tended to be more productive and performed better at simulated office tasks, such as text-typing, arithmetic and proof-reading.[30,63] An office with better air quality was also showed to be beneficial for occupants' health (typically shown by a reduction of SBS symptoms). Aside from better performance, Wargocki et al.[30] (see also [64]) also observed that participants reported higher frequency and more severe headaches, when the office had poorer air quality, during tasks that typically required concentration, such as arithmetic and text-typing. They subsequently observed that participants' reports of headaches decreased after a pollution source was removed from the office. In some cases, even though individuals might not have perceived the air quality of the office to be poor, it may still have affected their cognitive performance and health (reporting more SBS symptoms).[65] Another field study[66] at an office of a call-centre in Denmark found that when more fresh outdoor air (i.e. increased ventilation rate) in tandem with a brand new air filter, was introduced to the call-centre, work performance of the call operators improved and less SBS symptoms (like nose irritation and arching eyes) were reported by the operators. However, solely replacing a new air filter may not be enough to have such effects. It was observed that replacing with a new air filter at lower ventilation rates did not affect performance of the call operators. On the contrary, there were more reports of certain SBS symptoms such as irritation of the nose and eyes.

Besides improving the objective air quality of a space, the (subjective) perception of the quality of the room is important as well.[67] Generally, occupants tend to be concerned about the air quality of the space since poor air quality can be detrimental to one's health and performance. These concerns are rapidly rising with the outspread of the COVID-19 pandemic. Hence, clear communication of the information regarding air quality of a space, by making this information accessible and available to all individuals using these spaces, is crucial. It was observed that occupants were likely to take action to improve the air quality (if feasible), when information was made accessible to them.[68] Thus, it might be beneficial to monitor or measure the indoor air quality of an UGS and make this information easily accessible for the room's occupants. This might allow for individuals to develop more positive attitudes about UGS and will be more likely to accept UGS.[11]

Given that air quality is flagged, by potential occupants, as a critical feature for an underground office, more attention should be placed on this domain when constructing or designing underground offices, especially if there is a lack of natural ventilation (such as windows or shafts). A study conducted interviews with underground workers, from four different cities of China, working in various underground workplaces.[45] Air quality was the most concerning environmental aspect of UGS and over half of the interviewees, from three out of the four cities, mentioned that the quality of air in their UGS was poor. In addition, workers were more satisfied when their UGS had adequate ventilation. Hence, having proper and adequate ventilation for an underground office space is required to ensure air remains free of pollutants. It might also be important to note that efforts to maintain good air quality is comparable between underground and aboveground spaces.[11]

Nevertheless, lack of windows for underground spaces also emerged to be an important issue, with late majority responders of Montreal and London being particularly sensitive to this matter. Windows have been found to be an important feature for a comfortable indoor environment since they affect occupants both physiologically and psychologically.[69,70] Generally, offices with windows are preferred over windowless environments.[71–73] A study investigated perceived importance of windows between underground and aboveground office workers in Japan and observed that workers rated importance of individual functional aspects of windows (mean rating) lower than the overall rating of importance of windows.[74] This suggested that workers considered windows to carry more than just functional purposes.[74]

However, windows in subsurface areas are different from conventional ones in many ways. For instance, they cannot provide direct views of nature and daylight and may have to look into shared communal spaces or other workspaces. For conventional aboveground offices, large windows tend to be preferred.[75] However, location and size of windows for underground offices may have to be designed differently. Large windows in underground offices may allow co-workers or supervisors to look through the window and compromise the perception of privacy.[26,71,76,77] In addition, other elements can be introduced for the UGS to replace windows. For example, views to nature can be arranged with the establishment of green and water elements underground and sunlight can be directed using mirrors or simulated daylight could give access to 'natural' light in UGS.[78]

Existing or future technology can offer advanced solutions to problems associated with underground/indoor spaces. With respect to lighting, artificial windows and dedicated daylighting systems have been suggested[79]. For instance, fiber-optics based daylight systems have been proposed for indoor spaces, with the additional benefit that they might offer higher luminous efficacy.[80,81] In terms of air quality, previous studies[82,83] suggested that increasing air movement rate in offices would enhance acceptability of perceived air quality and diminish the negative impact of high air temperature and humidity, as well as pollution level. This can be done through energy efficient methods such as personal or protective occupant ventilation.[84] For recirculated air, improvements in the efficiency of air cleaning methods (such as electret filters and ion emission technologies) are leading to cost effective improvements in air quality.[85–88] New advances in building materials can reduce emissions of volatile organic compounds and formaldehyde.[89] The trade-offs between energy saving measures and indoor air quality can also now be modelled before the design is finalised, and any identified issues can be proactively rectified.[90] Indoor greenery, if properly maintained and included in a large-scale manner, may offer a partial sustainable solution for indoor air quality improvement.[91–93]

4.1. Strength and limitations

Our study has a large sample of individuals that have been residing in one of the four cities at least for several years. The four cities chosen are major cities with very large populations that actively use underground spaces – and they plan to expand even more. This ensures that our participants have been adequately exposed to these cities and should have some experiences with their underground spaces/facilities (such as underground transit, retail, and leisure facilities), though these experiences may not be specifically with underground workspaces. Moreover, by including different cities, we examine perspectives that are not limited to a certain culture, country or city.

A major limitation of the study is that participants were only asked to visualise an UGS and did not move to an actual UGS for the study. However, social psychological research suggests that individual's attitude towards an object (stated preferences) are good predictors of their behaviour,[55] and are actually one of the only ways to assess prospective behaviours towards future (and some might say futuristic) plans. In addition, these cities do have extensive UGS, as mentioned above.

Our findings provide practical feedback and valuable insights on the urgent question of communicating, designing and constructing of UGS that are more desirable for the public. Such insights may alleviate the public's (possible) negative views and attitudes towards UGS, creating a better underground working environment and increase adoption of such spaces.

5. Conclusions

Cities have aggressively adopted UGS as a solution to space depletion; however, the construction and design of UGS have been mostly based on speculation and anecdotal evidence. Building UGS could be costly, at least in the short-term, but also has significant advantages and thus it is imperative for UGS design to be successful. Thus, a design that does not focus on occupants' needs might be detrimental for the whole endeavour of expanding cities vertically. Our study offers concrete answers on the priorities that architects, urban planners and researchers should focus on. Contrary to past beliefs, air quality emerged as the most important building performance aspect for UGS. Given that this is a critical element to consider when designing UGS, it may be beneficial to monitor and report air quality. To make underground offices more adoptable by prospective occupants, it is necessary not only to consider functional purposes in architectural design but also to place human needs and user preferences as a high priority. Overall, the present results can help policymakers, engineers, architects, urban planners and scientists alike to understand how UGS can be improved to accommodate worker preferences and thus solve or mitigate the problem of land shortage in cities.

6. Author Contributions

Hui Shan Yap: Data Curation (lead), Formal Analysis (equal), Validation (equal), Visualization (lead), Writing – Original Draft Preparation (equal), Writing – Review & Editing (lead). **Adam Charles Roberts**: Conceptualization (equal), Methodology (equal), Validation (equal), Writing – Original Draft Preparation (supporting), Writing – Review & Editing (supporting). **Chengwen Luo**: Conceptualization (equal), Data Curation (supporting), Formal Analysis (equal), Validation (equal), Writing – Original Draft Preparation (equal). **Zheng Tan**: Writing – Review & Editing (equal). **Eun Hee Lee**: Conceptualization (lead), Data Curation (equal), Formal Analysis (equal), Methodology (lead), Writing – Original Draft Preparation (equal), Writing – Review & Editing (equal). **Thuan-Quoc Thach**: Writing – Review & Editing (equal). **Kian Woon Kwok**: Conceptualization (equal), Funding Acquisition (equal), Methodology (equal), Resources (equal), Supervision (equal). **Chee Kiong Soh**: Funding Acquisition (lead), Project Administration (equal), Resources (equal), Supervision (supporting). **Josip Car**: Funding Acquisition (equal), Project Administration (equal), Resources (equal), Supervision (supporting), Writing – Review & Editing (supporting). **Georgios I. Christopoulos**: Conceptualization (lead), Funding Acquisition (equal), Methodology (equal), Project Administration (equal), Resources (equal), Formal Analysis (equal), Supervision (lead), Validation (equal), Visualization (supporting), Writing – Original Draft Preparation (equal), Writing – Review & Editing (equal).

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Supplementary Materials

Supplementary Table 1 Mean-based ranking of concerns of architectural features for underground working space for all cities.

	Singapore		London		Shanghai		Montreal	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Air quality	10.16	2.05	9.82	2.14	10.43	1.79	9.78	2.26
Temperature	8.57	2.43	9.10	2.07	8.70	2.52	8.54	2.37
Lack of windows	8.15	2.95	9.70	2.26	8.49	2.53	9.27	2.60
Evacuation	7.56	4.08	5.53	4.03	4.51	3.83	6.23	4.10
Lighting	7.5	2.52	8.73	2.37	9.79	2.20	8.83	2.38
Mobile signal quality	7.29	3.46	5.53	3.48	5.97	3.09	4.98	3.21
Humidity	6.46	2.24	6.38	2.25	6.52	2.32	6.33	2.36
Unawareness of events outside	6.13	3.80	5.73	3.64	4.79	3.20	5.50	3.63
Noise level	4.31	1.96	4.98	2.12	5.19	2.41	5.19	2.48
Amount of space	4.16	2.51	4.18	2.45	4.98	2.76	4.57	2.85
Interaction with people in other work spaces	3.98	2.76	4.01	2.59	4.23	2.74	4.35	2.83
Privacy	3.72	2.14	4.31	2.37	4.41	2.42	4.44	2.49
Valid N	983		289		312		388	

Supplementary Table 2 Rank order of architectural features in underground spaces by willingness to work underground spaces for all cities.

Singapore			London			Shanghai			Montreal		
Features	*R-index*	*Sig.*	Features	*R-index*	*Sig.*	Features	*R-index*	*Sig.*	Features	*R-index*	*Sig.*
Air quality			*Air quality*			*Air quality*			*Air quality*		
	69.90%	**		50.98%	n.s.		58.20%	**		55.40%	**
Temperature			*Windows*[1]			*Lighting*			*Windows*[1]		
	52.50%	n.s.		59.56%	**		63.21%	**		56.90%	**
Windows[1]			*Temperature*			*Temperature*			*Lighting*		
	50.73%	n.s.		53.73%	n.s.		52.22%	n.s.		54.06%	n.s.
Evacuation			*Lighting*			*Windows*[1]			*Temperature*		
	55.39%	**		76.15%	**		72.85%	**		74.75%	**
Lighting			*Humidity*			*Humidity*			*Humidity*		
	49.64%	n.s.		55.33%	*		55.42%	*		49.86%	n.s.
Mobile[2]			*Unawareness*[3]			*Mobile*[2]			*Evacuation*		
	59.51%	**		50.90%	n.s.		57.01%	**		53.88%	n.s.
Humidity			*Mobile*[2]			*Noise level*			*Unawareness*[3]		
	51.75%	n.s.		51.70%	n.s.		54.06%	n.s.		50.46%	n.s.
Unawareness[3]			*Evacuation*			*Space*[4]			*Noise level*		
	62.15%	**		51.16%	n.s.		53.73%	n.s.		54.61%	*
Noise level			*Noise level*			*Unawareness*[3]			*Mobile*[2]		
	54.56%	**		60.99%	**		56.95%	**		52.48%	n.s.
Space[4]			*Privacy*			*Evacuation*			*Space*[4]		
	53.76%	**		52.21%	n.s.		44.75%	n.s.		49.62%	n.s.
Interaction[5]			*Space*[4]			*Privacy*			*Privacy*		
	49.92%	n.s.		53.35%	n.s.		53.97%	n.s.		52.78%	n.s.
Privacy			*Interaction*[5]			*Interaction*[5]			*Interaction*[5]		

*p < .05, **p < .01, n.s. = Not Significant (p > .05).

[1]Windows refers to Lack of window [2]Mobile refers to Mobile Phone signal quality [3]Unawareness refers to Unawareness of events outside [4]Space refers to Amount of space [5]Interaction refers to Interaction with people in other workspaces.

Supplementary Table 3 Mean-based ranking of concerns of architectural features for underground working space by willingness to work in an underground office for all cities.

	Singapore				London				Shanghai				Montreal			
	Low W		High W		Low W		High W		Low W		High W		Low W		High W	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Air quality	10.32	1.86	10.08	2.13	9.45	2.35	10.11	1.91	10.39	1.89	10.48	1.69	9.54	2.49	9.93	2.09
Lack of windows	8.79	2.59	7.83	3.06	10.14	1.91	9.35	2.46	9.06	2.34	7.94	2.59	10.06	2.09	8.79	2.76
Temperature	8.72	2.42	8.50	2.43	8.85	2.14	9.30	2.01	8.26	2.63	9.11	2.34	8.25	2.15	8.72	2.49
Lighting	7.43	2.54	7.54	2.51	8.62	2.27	8.82	2.45	9.97	2.07	9.63	2.32	8.90	2.45	8.78	2.35
Evacuation	7.42	4.02	7.64	4.10	6.29	4.18	4.93	3.82	4.44	3.68	4.57	3.98	6.55	3.98	6.03	4.17
Mobile signal quality	6.59	3.44	7.63	3.42	5.04	3.44	5.93	3.47	5.75	3.00	6.19	3.17	4.60	3.07	5.22	3.29
Unawareness of events outside	6.51	3.71	5.94	3.83	6.21	3.63	5.34	3.62	5.61	3.29	3.99	2.90	6.07	3.61	5.15	3.60
Humidity	6.40	2.24	6.50	2.24	6.16	2.22	6.55	2.27	6.33	2.36	6.70	2.27	6.07	2.25	6.49	2.41
Interaction with people in other workspaces	4.18	2.78	3.89	2.75	4.16	2.65	3.88	2.54	4.66	2.85	3.81	2.57	4.50	2.86	4.25	2.81
Noise level	4.12	1.93	4.40	1.97	4.76	1.87	5.16	2.29	4.73	2.43	5.62	2.33	4.84	2.32	5.40	2.55
Amount of space	4.04	2.46	4.22	2.53	4.33	2.56	4.07	2.36	4.75	2.74	5.20	2.78	4.40	2.92	4.67	2.81
Privacy	3.49	1.95	3.84	2.22	3.98	2.53	4.57	2.22	4.07	2.24	4.75	2.55	4.22	2.44	4.58	2.52
Valid N	323		660		128		161		153		159		148		240	
	983				289				312				388			

Note: W refers to willingness to work in an underground office.

Supplementary Table 4 Rank order of architectural features in underground spaces by willingness to work underground spaces for Singapore.

Features	Low Willingness		Features	High Willingness	
	R-index	*Sig.*		*R-index*	*Sig.*
Air quality	68.54%	**	*Air quality*	69.75%	**
Lack of windows	51.89%	n.s.	*Temperature*	54.76%	**
Temperature	64.26%	**	*Lack of windows*	47.73%	n.s.
Lighting	46.07%	n.s.	*Evacuation*	52.05%	n.s.
Evacuation	57.42%	**	*Mobile signal quality*	53.60%	*
Mobile signal quality	50.36%	n.s.	*Lighting*	62.75%	**
Unawareness of events outside	52.62%	n.s.	*Humidity*	53.86%	*
Humidity	74.70%	**	*Unawareness of events outside*	59.19%	**
Interaction with people in other work spaces	46.60%	n.s.	*Noise level*	55.11%	**
Noise level	53.46%	n.s.	*Amount of space*	55.60%	**
Amount of space	55.32%	*	*Interaction with people in other work spaces*	47.55%	n.s.
Privacy			*Privacy*		

*p < .05, **p < .01, n.s. = Not Significant (p > .05)

Supplementary Table 5 Rank order of architectural features in underground spaces by willingness to work underground spaces for London.

Features	Low Willingness		Features	High Willingness	
	R-index	*Sig.*		*R-index*	*Sig.*
Lack of windows	58.11	*	*Air quality*	58.28	**
Air quality	59.25	*	*Lack of windows*	52.47	n.s.
Temperature	52.61	n.s.	*Temperature*	54.53	n.s.
Lighting	64.80	**	*Lighting*	75.21	**
Evacuation	50.37	n.s.	*Humidity*	55.37	n.s.
Unawareness of events outside	51.64	n.s.	*Mobile signal quality*	55.81	n.s.
Humidity	60.87	**	*Unawareness of events outside*	49.54	n.s.
Mobile signal quality	48.98	n.s.	*Noise level*	54.79	n.s.
Noise level	57.67	*	*Evacuation*	48.67	n.s.
Amount of space	52.72	n.s.	*Privacy*	58.17	*
Interaction with people in other work spaces	51.50	n.s.	*Amount of space*	53.92	n.s.
Privacy			*Interaction with people in other work spaces*		

*p < .05, **p < .01, n.s. = Not Significant (p > .05)

Supplementary Table 6 Rank order of architectural features in underground spaces by willingness to work underground spaces for Shanghai.

Features	Low Willingness		Features	High Willingness	
	R-index	*Sig.*		*R-index*	*Sig.*
Air quality	55.69	n.s.	*Air quality*	60.77	**
Lighting	62.59	**	*Lighting*	57.09	*
Lack of windows	59.04	**	*Temperature*	63.05	**
Temperature	70.91	**	*Lack of windows*	65.49	**
Humidity	55.50	n.s.	*Humidity*	55.25	n.s.
Mobile signal quality	52.65	n.s.	*Mobile signal quality*	54.56	n.s.
Unawareness of events outside	57.07	*	*Noise level*	57.29	*
Amount of space	49.02	n.s.	*Amount of space*	53.68	n.s.
Noise level	52.76	n.s.	*Privacy*	57.58	*
Interaction with people in other work spaces	56.05	n.s.	*Evacuation*	48.23	n.s.
Evacuation	47.32	n.s.	*Unawareness of events outside*	49.85	n.s.
Privacy			*Interaction with people in other work spaces*		

*p < .05, **p < .01, n.s. = Not Significant (p > .05)

Supplementary Table 7 Rank order of architectural features in underground spaces by willingness to work underground spaces for Montreal.

Features	Low Willingness		Features	High Willingness	
	R-index	*Sig.*		*R-index*	*Sig.*
Lack of windows	55.12	n.s.	*Air quality*	62.06	**
Air quality	59.68	**	*Lack of windows*	51.81	n.s.
Lighting	60.11	**	*Lighting*	50.35	n.s.
Temperature	60.84	**	*Temperature*	74.56	**
Evacuation	52.90	n.s.	*Humidity*	52.93	n.s.
Unawareness of events outside	51.36	n.s.	*Evacuation*	53.19	n.s.
Humidity	66.54	**	*Noise level*	54.08	n.s.
Noise level	55.41	n.s.	*Mobile signal quality*	52.32	n.s.
Mobile signal quality	49.88	n.s.	*Unawareness of events outside*	50.98	n.s.
Interaction with people in other work spaces	51.34	n.s.	*Amount of space*	49.31	n.s.
Amount of space	49.47	n.s.	*Privacy*	55.58	n.s.
Privacy			*Interaction with people in other work spaces*		

*p < .05, **p < .01, n.s. = Not Significant (p > .05)