scientific reports

Check for updates

OPEN

Towards the Vertical City: psychosocial mechanisms for human-centered underground office spaces

Eun Hee Lee[1], Adam Charles Roberts[2], Kian-Woon Kwok[3], Josip Car[4], Chee-Kiong Soh[5,6] & Georgios Christopoulos[7]✉

Underground office workspaces (UOW) have emerged as a sustainable option in land-scarce megacities. Yet, the main challenge is to design and manage underground spaces that cater to the psychological needs of occupants. By integrating insights from social psychology, urban studies, and policy making, we identify and provide evidence for a key psychological mechanism underlying the adoption of UOW: "locus of control", a psychological process that reflects whether people feel in control of their environment or see it as shaped by external forces. Study 1 (N = 1093) revealed that individuals who believe external forces strongly impact their lives tend to have more negative attitudes toward working at UOW, perceiving negative aspects of the underground environment (e.g., confinement) as more salient. Study 2 (N = 217) builds on the findings of Study 1 by demonstrating that individuals who feel strongly influenced by external forces actively avoid UOW as their workplace, as evidenced by differences in locus of control between current underground and aboveground office workers. The present findings uncover a key psychological mechanism that can facilitate the adoption of UOW and invites engineers, designers and management to develop UOW environments that promote a sense of control and autonomy, fostering sustainable and occupant-friendly urban infrastructure.

Keywords Underground office workspace, Locus of control, Perception of control, Psychological mechanism, Human-centered design, Sustainable urban planning

The idea of extending the typical workplace to subterranean environment was initially an option seriously considered (and adopted) by countries with specific problems - such as Japan, a country with cities with very high population density and continuously rising land prices[1]; or countries with subarctic climates with relatively extreme weather conditions[2]. However, a combination of recent climatic[3], urban[4] and macroeconomic[5] changes have led many cities to actively examine the possibility of having underground office workspaces (UOW) as a pragmatic solution with many advantages: UOW can free-up more surface land in cities, protect occupants from various harmful environmental conditions, and overall meet the sustainability goal by reducing carbon emission associated with urban sprawl[6–8] and preserving natural landscapes[9]. Given the United Nations' forecast that the global urban population will constitute 68% by 2050[10], the development and significance of sustainable urban UOWs are gaining momentum as an integral element for accommodating the needs of the expanding urban workforce.

To date, the technological and engineering aspects of UOW have been extensively researched and evolved to meet the physical needs of the space (e.g.,, air ventilation, lighting conditions, environmental safety[11–13] while prioritizing environmental sustainability (e.g., high energy conservation measures[14]). Yet sustainable urban development, as the United Nations – Habitat agenda (2016) stated, places a strong emphasis on human well-being and active participation as critical elements in the pursuit of sustainable urban environments[15]. UOW, in

[1]School of Psychology, University of Nottingham Malaysia, Semenyih, Malaysia. [2]ETH Zurich, Future Resilient Systems, Singapore-ETH Centre, Singapore, Singapore. [3]School of Social Sciences, Nanyang Technological University, Singapore, Singapore. [4]Department of Population Health Sciences, King's College London, London, UK. [5]School of Civil Engineering, Southeast University, Nanjing, China. [6]School of Civil and Environmental Engineering, Nanyang Technological University, Singapore, Singapore. [7]Nanyang Business School, Nanyang Technological University, 50 Nanyang Ave, Singapore 639798, Singapore. ✉email: cgeorgios@ntu.edu.sg

this context, also needs to adhere to the principles of respecting and incorporating the psychological needs of occupants. However, research that looks into the human psychological perspectives of UOW is rather sparse and limited. Hence, the current research aims to address this gap by investigating the psychological mechanisms that support the adoption of UOW within the framework of sustainable urban development.

It is generally assumed, with not much empirical evidence, that the public holds a negative view of underground environments. This view often stems from the feeling of confinement linked to the enclosed nature of underground spaces[16], which is inherently associated with diminished sense of control[2]. Such psychosocial characteristics of underground space are meaningful in the context of understanding people's reaction to UOW because an environment that limits personal control over the space and prevents effective self-regulation to accomplish needed goals could be perceived negatively and actively avoided[17]. In line with this, the social ecological perspective in environmental adoption[18] states that individual's capacity to exert control and cope with the environment are crucial factors of environmental evaluation, which subsequently affect people's willingness to interact with the environment[19,20].

Drawing upon the association between the significance of 'control' in evaluating spaces and the enclosing features of underground environments that may diminish control[16,18,21], it can be inferred that perceived control forms a central aspect of psychological reactions to underground occupancy. This research aims to empirically assess the proposition by investigating the relationship between individuals' sense of control and the adoption of UOW. A two-fold study design is implemented to examine the phenomenon, and strengthen its ecological validity: in Study 1, we investigate the relationship between a psychological trait that relates to one's sense of control and the attitude toward UOW and, in Study 2, we examine the contribution of this trait in employees' actual decisions to work in UOW *retrospectively* by comparing employees' sense of control of current underground and well-matched aboveground working populations. Through this, we examine whether the psychological mechanism suggested to be important by a *prospective* move (Study 1) also persists and plays a central role in the *actual* adoption of the space (Study 2), enhancing the ecological validity of the identified mechanism.

General perception of underground spaces

Traditionally, an underground space is known as an enclosed space below the surface of the earth. Due to its location, there is no direct path to the external environment unless through designated exits[16]. Thus, typical but not necessary attributes of built underground environment include lack of windows, loss of contact with nature, and dark space[2]. These architectural limitations have been suggested to be related to specific profiles of psychological characteristics. For instance, lack of windows prevents the visibility of any landmark around the area, making harder to locate oneself and to way-find within the structure, which could leave occupants feeling lost. Moreover, a number of actions (e.g. opening windows for ventilation, adjustment of curtains to control natural light access) are restricted which could reduce the amount of control occupants have over the environment[22]. Darker luminosity as well as uniform architecture of the space can further worsen one's feeling of confidence and certainty within the space[2]. Additional associations often discussed include lifelessness, isolation, entrapment, and stagnation[21,23,24]. Although contemporary underground spaces have addressed numerous architectural challenges via engineering and technological advancements, there remains a prevalent public perception rooted in these old-fashioned views of subterranean environments, notably associating them with a loss of control.

More recent research has attempted to analyze psychological reactions to underground work environments systematically by identifying the foundational attitudinal factors that underpin these reactions. According to Lee et al. (2019)[25], these psychological reactions are primarily rooted in three key attitudinal factors: *calmness/safety*, *negative affect*, and *confinement*. The calmness/safety factor generally reflect positive attitudes towards underground workspaces, such as feelings of comfort, protection, and stability, which presumably stem from the protection underground structures can offer from various uncertainties aboveground. Negative affect captures negative emotional responses to underground workspaces, including fear, nervousness, and loneliness, which stem from the perceived isolation, restricted spaces, and potential risks associated with such settings. Lastly, confinement represents thoughts and understanding associated with the confining attributes of underground spaces, such as believing that the space lacks air or the space is associated with negative cultural connotations that are related to being confined below the ground level (e.g., 'staying inside a tomb'). This foundational analysis suggests that both positive and negative attitudes toward underground built environments are tied to the concept of encapsulation. Here, encapsulation can represent either a protective separation from the broader community, providing safety and comfort by shielding occupants from external stimuli, or a sense of confinement rooted in traditional perceptions of underground spaces—characterized by darkness, dampness, isolation, and restricted movement—that expose occupants to unfavorable environmental conditions[21,25]. The extent to which these aspects are perceived to a greater or less degree may vary depending on individuals' characteristics, experiences, and overall tendencies in perceiving their environment. Building on the earlier discussion highlighting the importance of perceived control in evaluating UOW, we propose that Locus of Control (LoC)—a personality trait reflecting an individual's sense of control—will influence their attitudes toward UOW, affecting the level of Safety/Comfort (positive), Negative Affect (negative), and Confinement (negative) felt toward the environment.

Locus of control: perception of control

LoC is a type of personality trait that reflects the degree to which people believe that they can determine their own environment and/or bring desired outcomes as opposed to external forces[26,27]. When LoC is located internally, the person believes the source of control is within themselves and that events in their life are determined by their own actions, reflecting a sense of mastery and self-efficacy. On the other hand, when LoC is located externally, individuals believe that control lies outside of themselves, attributing outcomes in their life to external factors

such as luck, fate, or the influence of others. This external orientation often leads to a perception of limited personal agency and a reliance on external circumstances to shape their experiences. In the literature on LoC, scholars often divide this construct into two independent components: internal LoC (reflecting the extent to which individuals believe control resides within themselves) and external LoC, (representing the extent to which individuals believe control lies outside of themselves). This distinction is used to capture these two aspects in detail, as they may not always correlate, thereby providing a clearer and more accurate understanding of a person's overall sense of control[28].

LoC plays a crucial role in shaping various life outcomes, with internal and external orientations influencing different aspects of an individual's experiences. An internal LoC, where individuals believe they control their life outcomes, is linked to positive outcomes such as higher well-being, academic success, and resilience to adversity[29]. It fosters motivation, achievement, and life satisfaction, acting as a buffer against negative events like illness or crime victimization, although it may not mitigate long-term economic impacts[30]. Internal LoC also supports pro-social behaviors and better coping, with factors like parental supervision aiding its development in children[31]. Conversely, an external LoC, where individuals perceive their lives as controlled by external forces, is often linked to negative outcomes such as poor academic performance, stress, and mental health challenges[32,33]. Together, these findings reveal the complex role of LoC, with internal LoC generally promoting adaptive behaviors and external LoC highlighting vulnerabilities in certain contexts.

While there has been limited research on the connection between LoC and responses to the physical environment, one study found that individuals with a more external LoC orientation often arrange their personal office spaces to minimize their visibility to visitors. This behavior is likely a defensive measure aimed at reducing the potential stress from unpredictable interactions with visitors[34]. In other words, individuals with a greater degree of external LoC, who feel less capable of managing situations, actively re-arranged their workspace to create an environment that offered greater control over interactions with visitors, thereby improving their ability to manage stress during their occupancy. Retrospectively, giving more control over the environment to individuals was suggested to increase satisfaction with the space[35], which contributes to the future engagement with an environment positively[36]. Thus, individuals' beliefs about their capacity to control situations and surroundings, as reflected by their LoC, may significantly influence how they form attitudes toward their immediate physical environment and how they interact with it. In particular, in environments like UOW, which inherently feature architectural elements that can diminish one's sense of control, LoC may serve as a central psychological determinant of whether a person is able to adapt to and accept such spaces.

The present study and hypotheses

This research investigates the link between individuals' LoC and the adoption of UOW through a two-part study: Study 1 investigates whether LoC influences attitudes toward UOW, while Study 2 examines its role in actual decisions to work in UOW by comparing current underground and aboveground employees' degree of LoC (refer to the flowchart in Fig. 1 for an overview of the general progression of the entire research). Drawing upon the discussion, individuals with an externally oriented LoC might view UOW less favorably, perceiving its inherent features that are unfamiliar and confining (which restricts control) as more challenging and harder to manage compared to those with an internally oriented LoC, who typically show greater resilience to external environments. Accordingly, we posit the following hypotheses on the relationship between internal and external LoC[42], and the three factors of the attitude toward UOW (calmness/safety, negative affect, and confinement) proposed by Lee et al.[25]. The hypothesis models are presented in Fig. 2:

Hypothesis 1a Internal LoC is negatively related to negative affect toward underground workspaces.

Hypothesis 1b Internal LoC is negatively related to confinement related thoughts about underground workspaces.

Hypothesis 1c Internal LoC is positively related to calmness / safety perception toward underground workspaces.

On the other hand, we predict the opposite pattern of relationships for external LoC as below:

Hypothesis 2a External LoC is positively related to negative affect toward underground workspaces.

Hypothesis 2b External LoC is positively related to confinement related thoughts about underground workspaces.

Hypothesis 2c External LoC is negatively related to calmness / safety perception toward underground workspaces.

Moreover, it is speculated that LoC not only shapes how individuals perceive and form attitudes toward UOW but also influences their choice of work location based on their perceived capacity to manage and cope with UOW according to their level of LoC. Viewed retrospectively, this suggests that the degree of LoC among today's workforce varies based on their office location—underground or above ground—reflecting their perceived ability to manipulate their environments to achieve desired outcomes. Following this, we present the hypotheses on the levels of internal and external LoC of the two working populations based on the location of office (see Fig. 3):

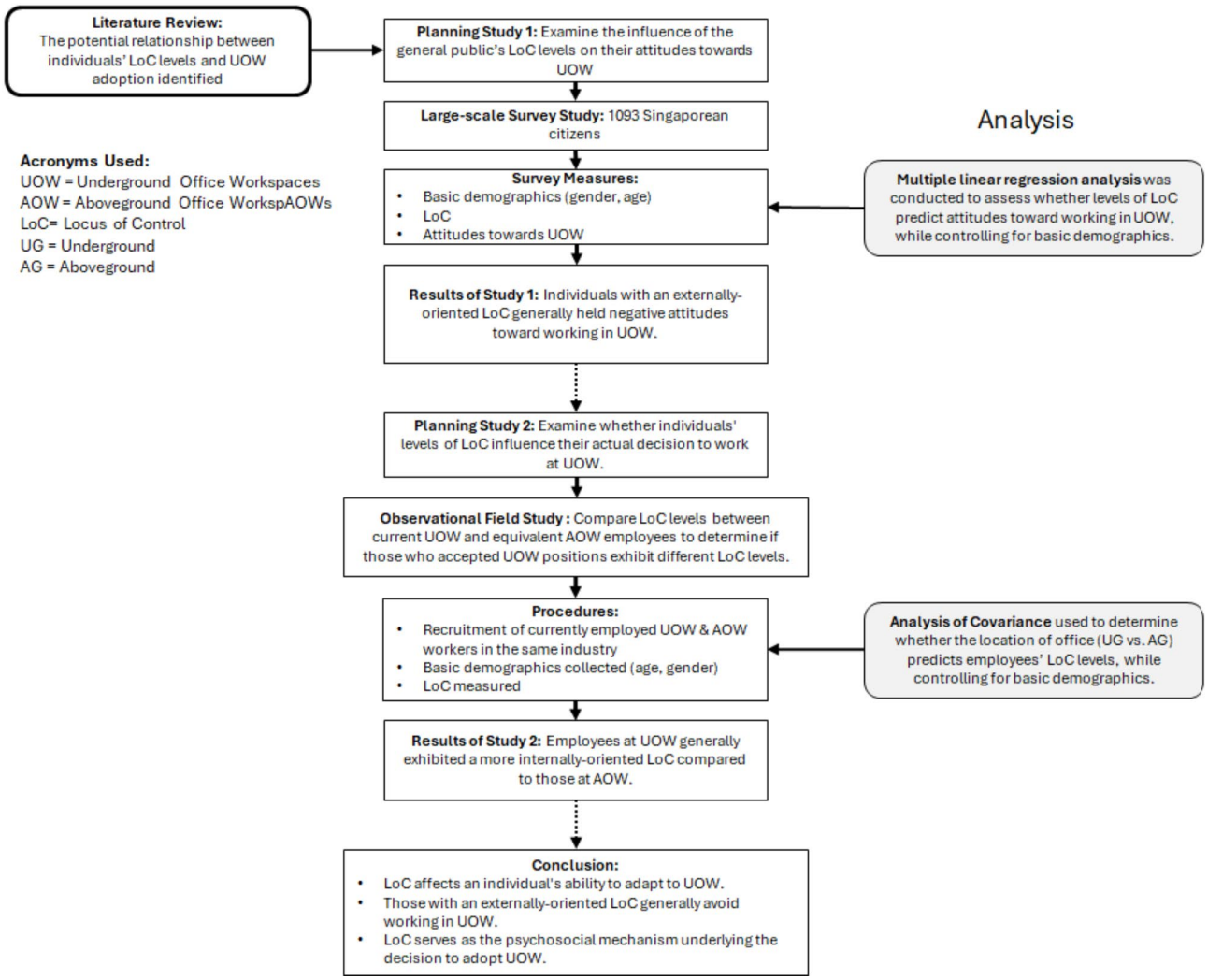

Fig. 1. Flow chart of an overview of the general progression of the entire research.

Hypothesis 3a Individuals working in underground offices have a greater degree of internal LoC compared to those working in comparable aboveground offices.

Hypothesis 3b Individuals working in underground offices have a lesser degree of external LoC compared to those working in comparable aboveground offices.

In addition, we suggest that the duration of employment serves as a critical moderator influencing the LoC variation of employees based on office location. As employment duration increases, LoC variation is likely to widen as prolonged interaction with the office environment enables employees to fully evaluate their adaptability, ultimately influencing their continued occupancy at the workplace. Employees who cannot adapt to and cope with UOW due to a relatively higher external LoC and lower internal LoC are expected to be selected out further (e.g. leave the current employer or re-locate). In other words, over time, employees in UOW with a more internally oriented LoC, who have a stronger belief in their ability to control their situations and environment, are more likely to remain in the workplace. Thus, we present the next hypothesis on the moderating effect of employment duration on the predictability of work location in LoC levels.

Hypothesis 4 As employment duration increases, the differences in internal and external LoC between employees working in underground and aboveground offices become more pronounced, aligning with the directions described in Hypotheses 3a and 3b.

Study 1 aimed to investigate and establish the link between individuals' LoC orientation and the attitudes toward UOW. A large-scale survey was conducted with the general public of Singapore to examine the relationship between internal and external LoC with each attitude factor, calmness/safety, negative affect, and confinement[25], toward a hypothetical deep UOW to gain an insight into the psychological reaction of prospective employees of UOW.

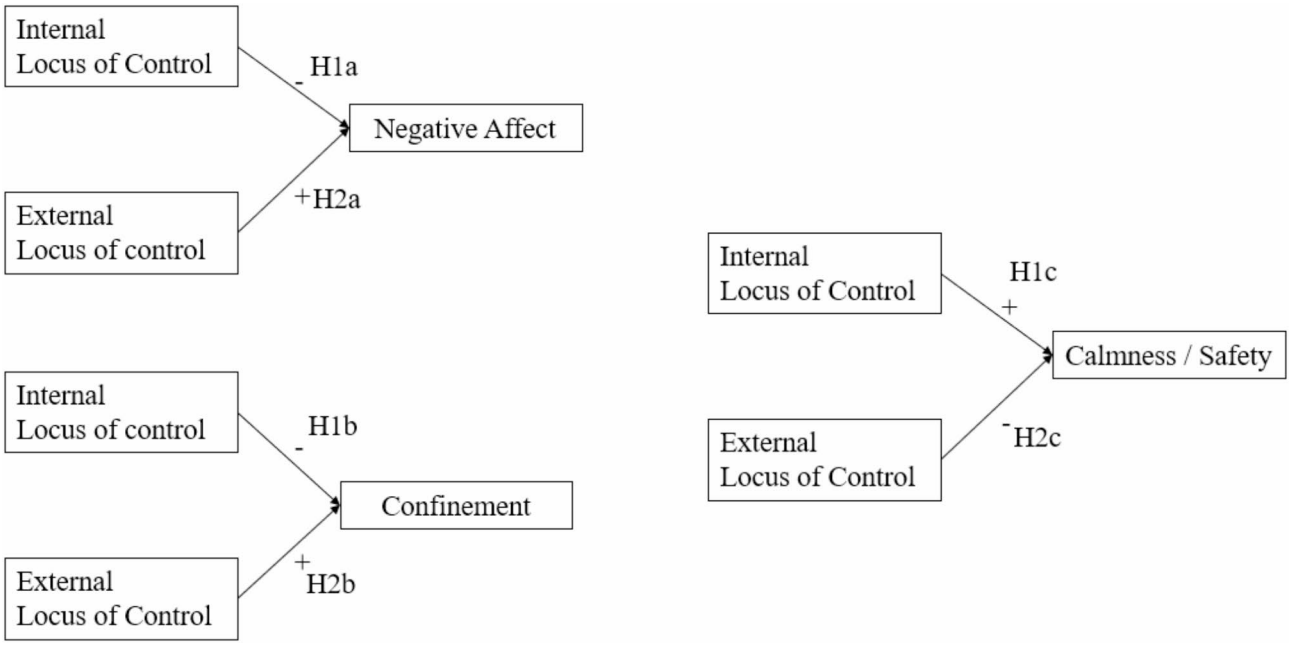

Fig. 2. Hypothesized models for study 1.

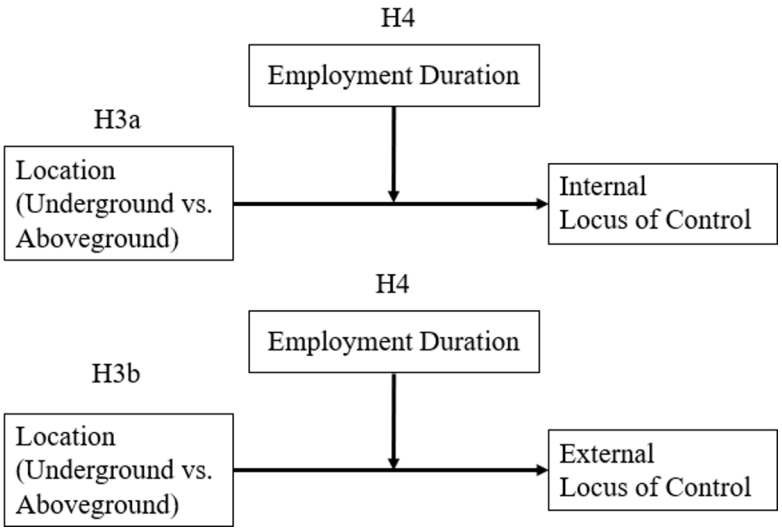

Fig. 3. Hypothesized models for study 2.

Study1

Method

Sample

The sample, comprised of 1093 Singaporean citizens and permanent residence holders (women: 548 (50.1%)), was recruited through a specialized market research company, Qualtrics, and was administered an online survey using the Qualtrics platform. In terms of ethnicity, 71.6% were Chinese, 14.9% were Malay, 10.2% were Indian, and 3.2% were others, which was matched to the ethnic diversity of Singapore. Mean age was 36.07 years (SD = 11.21).

Ethics statement

Informed consent was obtained from all the survey participants, the anonymity of the participants was ensured and collected data was kept confidential. Before starting the study, the Institutional Review Board of Nanyang Technological University (the central ethics committee) reviewed and approved our study procedures. The study followed the Declaration of Helsinki guidelines for all procedures involving human subjects.

Measure

Locus of control LoC was measured using Levenson's locus of control scales[37]. The internal LoC scale (α = 0.76) measures the extent to which individuals believe reinforcements as contingent on their own behavior, hence, the degree to which control is internal. The external (chance) LoC scale (α = 0.78) measures the belief that experiences and outcomes are controlled by chance or luck, reflecting the extent to which control is determined by external factors. One of the items in each scale was written in the context of car accident for the general population. However, given the low private car ownership rate in Singapore[38], these context-based items were omitted. Participants rated on a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree).

Attitudes toward working in underground workspace Perception toward working underground was measured by the underground workspaces questionnaire (UWSQ; Lee et al., 2019). The UWSQ assesses pre-occupant attitudes toward underground workspaces, and is comprised of three factors, namely, *calmness/ safety*, *negative affect*, and *confinement*. The calmness/ safety factor measures the view on positive aspects of underground spaces, reflecting both affective and practical considerations. The negative affect factor consists of items that depict negative affective states. In other words, the question asks how the respondent would *feel* if they were working in an underground office (e.g. nervous, lonely, and distracted). The confinement factor reflects negative *beliefs* in relation to the elements of confinement of the underground workspace, such as concern about air quality and associated negative cultural beliefs (e.g. burial and evil). Participants rated 16 items in total on 7-point Likert scales (1 = Strongly Disagree to 7 = Strongly Agree).

Data availability

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

Results and short discussion for study 1

Table 1 presents the means, standard deviations, and simple correlations between each attitude factor of UWSQ (Calmness/ Safety, Negative Affect, Confinement), and internal and external LoC. For the main analyses, linear regressions were conducted to determine whether internal and external LoC (predictor variables) predict the attitudes toward working underground (dependent variables): Calmness / Safety, Negative Affect, and Confinement. Age and gender were included as control variables because they are widely recognized in social, behavioral, and psychological research as key demographic factors influencing outcomes. Controlling for these variables ensures that observed effects are not confounded by demographic differences. Moreover, in the context of architectural studies, research indicates that women often perceive environments in greater detail, prioritising aspects such as cleanliness, aesthetics, and safety, while men may focus more on connectivity[39]. Gender differences also extend to sensory and neurological responses to architectural settings[40]. Likewise, age influences environmental perceptions, with older adults placing greater importance on personal control, comfort, and space usage, whereas younger individuals value environments that support teamwork[41]. Thus, including age and gender accounts for potential variability in responses and enhances the robustness of the analysis.

First, negative affect toward the underground office was tested as the outcome variable. The results showed that external LoC (β = 0.222) was associated with negative affect, supporting Hypothesis 1b, but internal LoC was not associated with negative affect, hence Hypothesis 1a was not supported. This implies that people who exhibit greater external LoC in particular had more negative affect toward the underground office (see Fig. 4; Table 2).

Next, perceived confinement toward the underground office was tested as the outcome variable. External LoC was a significant predictor (β = 0.161) of perceived confinement, supporting Hypothesis 2b. As in the previous analysis, internal LoC was not associated with perceived confinement toward the underground office so our Hypothesis 2a was not supported (see Fig. 4; Table 3).

Lastly, calmness / safety perception toward the underground office was tested as the outcome variable. The results revealed that there was no main effect of any of the LoC variables, which suggests that LoC variables were not associated with the perception of calmness and safety toward the underground office. Therefore. Hypothesis 3a and 3b were not supported (see Fig. 4; Table 4).

The findings generally support our hypotheses, showing that the degree of LoC influences attitudes toward UOW. Specifically, individuals with a greater degree of external LoC, who feel overpowered by external forces, exhibit more negative feelings toward working in UOW (negative affect) and perceive the environment as more confining (confinement). On the other hand, internal LoC had no predictive values in attitudes toward UOW, suggesting that an individuals' belief in their ability to manage situations plays a less critical role in shaping

	Variable	M	SD	*N*	1	2	3	4
1	Negative Affect	3.95	1.24	1093				
2	Confinement	4.45	1.16	1092	0.66**			
3	Calmness/ Safety	3.56	0.97	1090	−0.38**	−0.43**		
4	Internal Locus of Control	3.74	0.52	1092	−0.05	−0.02	0.05	
5	External Locus of Control	3.02	0.65	1092	0.21*	0.16**	0.07*	−0.04

Table 1. Means, Standard Deviations, and correlations. M, SD, and N are used to represent mean, standard deviations and sample size, respectively. *Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed).

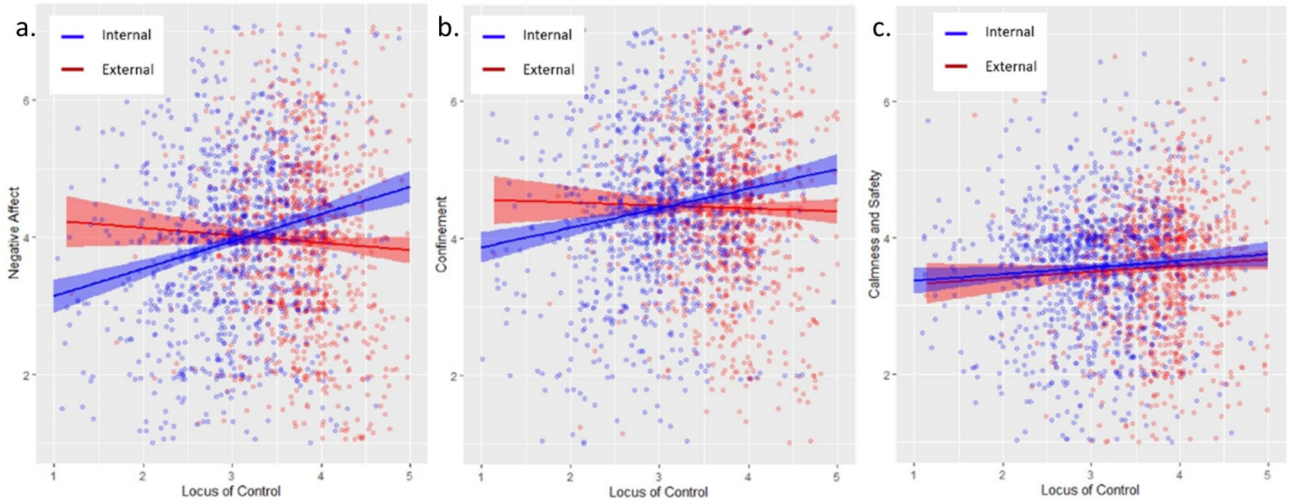

Fig. 4. The Relationship between (**a**) Negative Affect, (**b**) Confinement, and (**c**) Perceived Calmness and Safety toward Underground Workspaces and Locus of Control (Internal and External). Higher levels of internal and lower levels of external (chance) locus of control are associated with more negative attitudes (affect and confinement) toward working in UOW. There is no effect on positive aspects (calmness).

Variable	B	95% CI	Beta (β)	t	*p*
Gender	− 0.335	[-0.450, -220]	− 0.173	-5.701***	0.000
Age	− 0.007	[-0.012, − 0.002]	− 0.084	-2.776**	0.006
Internal locus of control	0.076	[-0.033, 0.185]	0.041	1.370	0.171
External locus of control	0.085	[-0.003. 0.173]	0.057	1.896	0.058

Table 2. Summary of regression analysis for the effect of locus of control on calmness/safety perception. $F(4,1082) = 11.015$, $p < .001$, $R^2 = 0.039$, $^*p < .05$; $^{**}p < .01$; $^{***}p < .001$.

Variable	B	95% CI	Beta (β)	t	*p*
Gender	0.455	[0.310, 0.599]	0.183	6.181***	0.000
Age	0.000	[-0.006, 0.007]	0.002	0.071	0.943
Internal locus of control	− 0.048	[-0.185, 0.089]	− 0.020	− 0.689	0.491
External locus of control	0.405	[0.295, 0.515]	0.211	7.224***	0.000

Table 3. Summary of regression analysis for the effect of locus of control predicting negative affect. $F(4,1085) = 22.792$, $p < .001$, $R^2 = 0.078$, $^*p < .05$; $^{**}p < .01$; $^{***}p < .001$.

Variable	B	95% CI	Beta (β)	t	*p*
Gender	0.293	[0.1156, 0.431]	0.126	4.191***	0.000
Age	− 0.006	[-0.012, 0.000]	− 0.060	-1.986*	0.047
Internal locus of control	0.008	[-0.123, 0.138]	0.003	0.113	0.910
External locus of control	0.285	[0.181. 0.390]	0.159	5.348***	0.000

Table 4. Summary of regression analysis for the effect of locus of control on perceived confinement. $F(4,1084) = 13.408$, $p < .001$, $R^2 = 0.047$, $^*p < .05$; $^{**}p < .01$; $^{***}p < .001$.

attitudes compared to the perception of being influenced by external forces (external LoC). Lastly, perceived comfort and safety regarding UOW was not influenced by LoC.

Study 2

Study 1 revealed that the general public with an externally oriented LoC generally holds negative attitudes toward the idea of working in UOW. However, a key question remains: does LoC influence the actual decision to work in UOW? Study 2 aims to fill in this gap by examining the LoC of the current working population of underground and comparable aboveground offices to retrospectively determine whether differences in LoC are associated with their actual work environment choices. Thus, the internal and external LoC of the current underground and aboveground employees who work in the same industry were compared, based on the assumption that their choice of the current work location reflects the employees' psychological profiles that enabled the adoption of UOW. If people with predominantly external LoC (feeling controlled by outside forces) are reluctant to work underground, it is expected that the current underground working population will possess relatively internal LoC (feeling in control of their own lives) overall.

Method

Sample and procedure

Data were collected from a cohort of 217 participants between November 2016 and April 2017 at two time points. Initially, 75 workers from underground offices and 142 workers from aboveground offices participated in the study, but 7 participants from underground and 13 participants from aboveground offices dropped out of the study by the second round due to personal issues. In terms of ethnicity, 74.7% were Chinese, 9.2% were Malay, 12.0% were Indian, and 4.1% were others, which was representative of the ethnic diversity of Singapore. The mean age of participants was 38.40 ($SD = 11.67$). Our sample was predominantly male (69.1%, $N = 150$) due to the nature of the industry chosen (transport industry). Participants were invited to participate in the study via meetings, workplace posters, and emails. Those who expressed interest in participation were screened for eligibility based on the following criteria: aged 21 years and above, should be working for at least four hours per day at their stated workplace, and not pregnant. Participants were deemed ineligible if they made at least one trip per month to countries in a different time zone from Singapore in the past 6 months. Importantly, all our participants worked in the same sector of semi-governmental companies, with very similar job functions (office desk-bound job) with almost identical organizational characteristics (e.g. work hours and hiring practices), which greatly accounts for uncontrolled organizational differences.

Ethics statement

Informed consent was obtained from all the survey participants, the anonymity of the participants was ensured and collected data was kept confidential. Before starting the study, the Institutional Review Board of Nanyang Technological University (the central ethics committee) reviewed and approved our study procedures. The study followed the Declaration of Helsinki guidelines for all procedures involving human subjects.

Materials

Work site Four office buildings supporting two companies within the same industry in Singapore were selected as the study sites. These organizations had offices in either under- or aboveground environments or both. Indoor environmental quality parameters were all within the recommended levels (see Table 5 for general characteristics of different office layouts).

Locus of control As in Study 1, LoC was measured using Levenson's locus of control scale[42]. Again, the internal LoC scale ($\alpha = 0.79$) that measures the degree to which control is internal, and the external LoC scale ($\alpha = 0.78$) which measures the belief that experiences, and outcomes are controlled by chance or luck (externally oriented), were administered.

Data availability

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

Results and short discussion for study 2

Univariate general linear models (GLM) were used to examine the differences in LoC of those who work in underground and aboveground offices: the location of the office (2: aboveground vs. underground) was the independent variable and the two types of LoC (Internal and external) were dependent variables. Specifically,

Location	Characteristics
Aboveground	Shared offices (35–42 m^2, 3–5 staff); Open-plan offices (120–180 m^2, 40–50 staff) Ceiling height: 2.70–2.95 m Window size: 1.5 m x 1.7 m; 1.6 m x 1.5 m; 2.1 m x 1.5 m An individual cubicle with 0.70 m x 1.20 m desktop area partitions at a height of 1.10–1.45 m (or no partition)
Underground	Shared offices (21–27 m^2, 2–6 staff); Open-plan offices (70–170 m^2, 32–75 staff) Ceiling height: 2.80–3.20 m An individual cubicle with 0.70 m x 1.20 m desktop area, partitions at a height of 1.20–1.55 m (or no partition)

Table 5. Characteristics of office layouts for underground vs. aboveground.

Predictor	Sum of squares	df	Mean square	F	*p*	Partial η^2	95% CI [LL, UL]
(Intercept)	144.746	1	144.746	462.451***	0.000	0.686	[3.552, 4.325]
Underground/ Aboveground	1.503	1	1.503	4.803*	0.029	0.022	[0.018, 0.343]
Age	0.089	1	0.089	0.286	0.594	0.001	[−0.011, 0.006]
Gender	0.158	1	0.158	0.505	0.478	0.002	[−0.231, 0.109]
Employment duration	0.044	1	0.044	0.141	0.707	0.001	[−0.001, 0.001]
Error	66.356	212	0.313				

Table 6. ANCOVA results for Internal Locus of Control. LL and UL represent the lower-limit and upper-limit of the confidence interval, respectively. $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

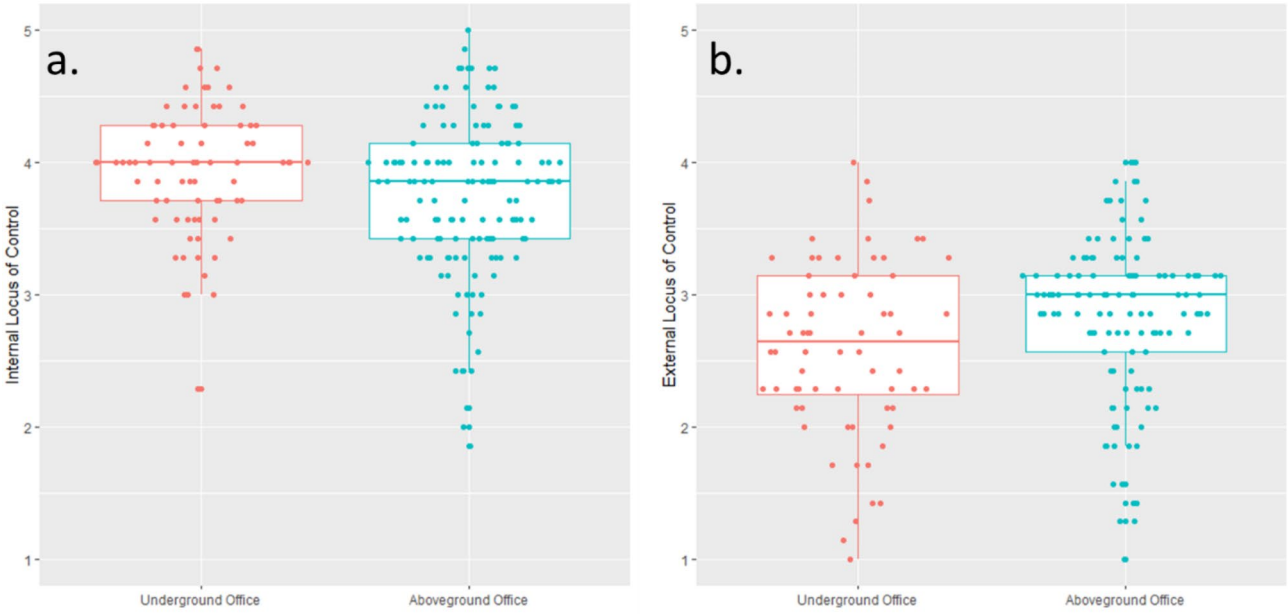

Fig. 5. Bar charts showing the differences in internal (**a**) and external (**b**) locus of control across under- vs. aboveground office workers. Underground office employees have higher internal locus of control and lower external locus of control.

for each of LoC (internal and external), we conducted an analysis of covariance (ANCOVA) that compared the effects of underground versus aboveground location on LoC after controlling for age and gender as in Study 1. In addition, we included the number of months the employees worked (duration of work) at the current location of company as a covariate to control for the effect of duration of work.

First, we examined the differences of internal LoC of underground vs. aboveground office workers. The results ANCOVA are presented below (Table 6; Fig. 5), suggesting that underground office workers had higher internal LoC score compared to aboveground workers, $F(1, 212) = 4.803$, $p = .029$, after controlling for age, gender, and employment duration. Thus, H3a was supported.

We then examined whether employment duration moderated the effect of office location on internal LoC, to determine if internal LoC levels became more extreme in the direction predicted by Hypothesis 3a as employment duration increased. A simple moderation analysis was performed using PROCESS macro in SPSS (a statistical tool designed to test complex models, such as moderation and mediation[43]). The dependent variable for analysis was internal LoC, and the independent variable was the location of office (underground vs. aboveground). Age and gender were entered as covariates to control for the effects. The results showed that the interaction between the location of office and work duration was non-significant [$B = -0.0009$, 95% C.I. (-0.0024, 0.0007), $p = .2592$], showing that the length of employment at the current location did not moderate the relationship between office location and internal LoC. Thus, H4 was not supported.

Moving on to the effect of office location on external LoC, we examined the differences in external LoC of underground office workers versus. aboveground office workers. The results of ANCOVA are shown below (Table 7; Fig. 5), indicating that the workers in underground offices scored lower in external LoC compared to the workers in aboveground offices $F(1,192) = 4.548$, $p = .034$, after controlling for age, gender, and work duration, supporting H3b.

Again, we checked whether employment duration moderated the predictability of office location on internal LoC using PROCESS macro. The dependent variable for the analysis was external LoC, and the independent

Predictor	Sum of squares	df	Mean square	F	*p*	Partial η^2	95% CI [LL, UL]
(Intercept)	51.307	1	52.968	131.366***	0.000	0.406	[2.127, 3.020]
Underground/ Aboveground	1.776	1	1.776	4.548*	0.034	0.023	[−0.397, −0.015]
Age	0.299	1	0.299	0.766	0.382	0.004	[−0.005, 0.014]
Gender	0.483	1	0.483	1.236	0.268	0.006	[−0.087, 0.312]
Employment duration	0.654	1	0.654	1.674	0.197	0.009	[−0.002 0.000]
Error	74.988	192	0.391				

Table 7. ANCOVA results for external locus of control. LL and UL represent the lower-limit and upper-limit of the confidence interval, respectively. $^*p < .05$; $^{**}p < .01$; $^{***}p < .001$.

variable was the location of office, with age and gender entered as covariates to control for the effects. The results showed that the interaction between the location of office and employment duration was non-significant [$B = -0.0001$, 95% C.I. (-0.0017, 0.0019), $p = .9028$], confirming that there was no moderating effect driven by the length of employment at the current location. Thus, H4 was not supported.

In short, the location of office (underground vs. aboveground) predicted both internal and external LoC of the current employees, such that those who work in underground offices exhibited more internally oriented LoC (i.e., high internal LoC and low external LoC) compared to those who work in aboveground offices. There was no moderation effect by employment duration for either LoC, suggesting that the actual experience of working in an underground office did not amplify the differences in LoC in the predicted directions.

Discussion

This research examined whether individuals' general sense of control, as reflected by the degree of internal and external LoC levels, is a fundamental psychological trait that influences the attitudes and acceptance of working in an UOW. Through an examination of the general public's attitude towards a hypothetical move to UOW (Study 1), as well as an observational study involving current aboveground and underground employees (Study 2), our findings suggest that individuals' sense of personal control serves as a significant predictor of the adoption of UOW. Specifically, Study 1 demonstrated that people who have externally oriented LoC had negative attitude toward UOW, while Study 2 demonstrated that those who currently work in UOW exhibited relatively internal LoC. These results collectively suggest that individuals who feel less capable of exerting control over their lives may find occupying UOW challenging and actively avoid such spaces.

Implications

The current research provides theoretical implications for understanding how psychological profiles affect interactions with the physical environment. Although both studies generally supported the main hypothesis that people with externally oriented LoC, believing that their lives are largely controlled by external forces or circumstances, are reluctant to the idea of working underground, the findings of Study 1 showed that only external LoC was a significant predictor of the attitudes toward UOW, when in Study 2, both internal and external LoC were shown to be significant predictors of UOW occupancy. These results shed light on an important aspect that distinguishes psychological processes underlying mere attitudes versus active interaction with a physical environment.

When a person evaluates an environment without commitment of interaction, as in Study1 (where participants only had to report their attitudes toward a hypothetical UOW), one's concern for action capacity within the environment may become less important because there is no need for one to realistically project their capacity to manage and survive the environment[17,18]. In this context, internal LoC, representing an individual's belief in their ability to influence outcomes, diminishes in significance in the evaluation process because the person does not expect to exert control over the environment (i.e., UOW). On the other hand, external LoC, which reflects an individual's perception of external constraints, is still likely to remain significant regardless of the level of interaction commitment, as this psychological construct originates from one's evaluation of external factors[26]. Thus, external LoC is expected to consistently predict evaluations of a physical environment, whether these evaluations involve interaction commitment or not, whereas internal LoC is significant only in cases involving interaction commitment. Accordingly, the findings of Study 2, where participants had already evaluated and committed to interacting with their physical environment, logically show that both internal and external LoC hold predictive value in their choice of office environment. To some extent, these results align with prior studies that suggested external LoC tends to be a more reliable predictor of subjective wellbeing[28,44]. Thus, it is recommended that scholars and practitioners in built environment pay more attention to external LoC as a key psychological factor in understanding prospective occupants' reaction to different environments.

The readers of this article should be careful in interpreting the current results on the association between LoC and UOW. While we argue that those with more externally oriented LoC are reluctant to accept UOW, presumably due to their perceived inability to control the environment, this proposition does not necessarily mean that working at UOW actually depletes one's control. Study 2 found that employment duration did not amplify the differences in LoC between the two office locations, suggesting that the UOW environment did not cause employees to leave their jobs or struggle to adapt due to their LoC. This suggests that UOW may not have as much of an impact on their ability to function or adjust to the environment as expected based on their pre-conceived beliefs or perceptions. Moreover, research examining various types of workers' satisfaction in

both underground and aboveground settings in the past found no difference in satisfaction with the physical work environment (e.g., lighting, air quality, humidity) between underground workers and their aboveground counterparts, regardless of job type[45]. Although it is too early to conclude, pre-conceived perception and beliefs about UOW might be the critical factor that underlies various negative psychological reactions and behavioral intentions toward UOW rather than the actual experience of being UOW.

Our studies contribute significantly to theoretical advancements in the psychology of underground spaces. Past research has highlighted an association of UOW with a generic, non-specific negative psychological sentiment. We here move forward by identifying a more precise, theoretically established and measurable mechanism to effectively answer the longstanding question of the exact reasons underlying the negative psychological associations – perception of control. The current research highlights that a very specific aspect of personality that relates to perceived control predicts how one views and adopts UOW: the consistency of key results across different populations in the two studies enhances external validity and generalizability, indicating that the mechanism applies in both prospective and actual occupants. While past literature on underground space has constantly brought the concept of perceived control as an essential psychological element that underlies various reactions toward underground spaces[2,16], it has not been directly tested until today. Thus, by outlining LoC as an essential trait that influences people's attitudes and adoption of UOW, our research extends somewhat limited literature of the psychology of underground spaces by empirically testing and confirming the crucial role of individuals' perceived control in understanding people's reaction toward underground environment.

In addition, from the perspective of LoC research, this research is one of the very few available studies that demonstrates the independent and direct effect of LoC on people's preference for physical environment. Earlier literature on LoC mostly discussed LoC as a key predictor for various well-being outcomes (e.g., job attitudes, affect, motivation and behavioral performance[46]). However, our findings demonstrate that LoC does not only affect one's reactions to situations but physical environments that they might need to interact. In this regard, LoC should be regarded as an important psychological variable in understanding how people navigate and utilize an environment, especially an environment that people might be unfamiliar with like UOW.

Interventions and practical applications

Even though LoC is a psychological trait, it can certainly be enhanced and "primed", especially by architectural or other interventions. Currently, the public seems to associate UOW with the traditional idea of underground environment that limits one's control, which has a pronounced effect on people with predominantly external LoC when deciding whether to adopt UOW. In essence, this implies that only a restricted number of people may ultimately embrace UOW as their workplace (if they had the freedom to choose), which could be unfavorable for enterprises located in subterranean settings. To reduce such bias, it is recommended to rebrand publicly accessible underground spaces to challenge and change outdated perceptions and beliefs about underground environments. Existing underground structures could be repurposed for a wider range of uses beyond their traditional roles as car parks, storage areas, or simple transitional spaces, enabling them to serve more diverse and innovative functions. For instance, urban farming, particularly hydroponics, is a potential use for multi-storey car-parking structures, offering social, environmental, and economic benefits[47]. The Lowline project in New York City, is also a good example that demonstrates the innovative use of abandoned underground spaces for public gardens, addressing urban challenges and enhancing city life by transforming idle spaces into green infrastructure with ecological, economic, and social benefits[48]. Moreover, when promoting these structures to the public, it may be more effective to emphasize their functionality rather than their underground location, to help challenge and reduce biases against such spaces. One way to achieve this is by renaming the floor levels of the building, for example, re-labeling B2 based on its relative position to the deepest level (e.g., B5 could become "Ground Floor," and B2 could be renamed as Level 4 to remove "B" designation). By not mentioning "basement," this approach could help dissociate the space from the idea of being underground, potentially reducing negative perceptions and feelings of confinement[21].

Alternatively, it may be beneficial to enhance existing underground workspaces by addressing architectural elements that contribute to feelings of confinement and loss of control, thereby improving overall perceptions of underground spaces. For instance, better lighting could be installed to expand the view of workers[49]; landmark-like features as well as maps that could better assist one's wayfinding within the building should be easily accessible to enhance one's sense of direction; greenery can be added to the indoor design to give more access to nature so that it reduces a sense of segregation from the rest of the world[50]; more spacious transitional spaces (e.g., corridors) should be adopted to decrease a sense of confinement[51], building of more exit routes, light wells, and artificial windows within the structure could enhance openness and provide a greater sense of safety and connection to the outside environment[21,52].

Moreover, to attract more people to jobs or offices already located underground, companies can focus on enhancing employees' control over their environment. Offering larger personalized spaces, allowing control over local ventilation, heating/cooling, and lighting intensity, and providing flexible working hours or remote work options can counter perceptions of underground spaces as restrictive and confining. These measures not only improve the experience for current employees but also make these roles more appealing to potential candidates.

Limitations and future directions

As with most research that examines relatively new phenomena in real-life working populations, there are some limitations with the present research. While our hypotheses assume that LoC influences perception toward UOW, and possibly impact potential employees' adoption of UOW, both our studies were observational studies that cannot confirm the causal link. Building on our empirical findings, we encourage future research to explore the causal relationship between LoC and workspace choice. This could begin with a lab-based experiment that examines how a manipulated sense of control influences workspace preferences while controlling for other

unknown variables. However, recognizing the limitations of lab studies in ecological validity, this field would greatly benefit from a large-scale longitudinal study that observes individuals over an extended period to examine whether LoC genuinely influences their choice of physical workplace environments, providing deeper insights into its long-term effects on job settings.

This paper examined two distinct populations across studies. Study 1 focused on prospective occupants (the general public) with limited or no experience in underground spaces, while Study 2 investigated actual occupants of such spaces. While the discrepancy between these populations for testing the link between LoC and the adoption of UOW could be considered a limitation—potentially affecting the results—it also serves as a strength. Testing the proposed mechanism in both groups enhances the generalizability of our findings by demonstrating how the same mechanism underlies both pre-beliefs about the space and the actual experience of the space.

As with all field studies, which inherently lack the precision and control achievable in laboratory settings, Study 2 faced challenges in achieving complete parity or strict control between the two groups (underground vs. aboveground). This introduces the possibility that external variables beyond our control may have influenced the results. Despite this, we made significant efforts to ensure the two populations were as comparable as possible. Both groups are employed within the same organization, share similar demographic characteristics such as age and gender, and work in office environments designed according to standardized organizational guidelines. These measures were implemented to mitigate the influence of uncontrolled factors and to emphasize the role of vertical location (underground vs. aboveground) in shaping the findings.

Lastly, the unique and rare sample of current underground and comparable aboveground office workers makes our Study 2 very special and ecologically valid. However, the participants were mostly males due to the type of industry they were in. While we did not find any gender effect in explaining the differences in LoC of the underground and aboveground office workers, it could still restrict our conclusions to a certain extent. Thus, we encourage future studies to explore participants of different industries where they have more balanced demographics to generalize the unique effect of LoC on the adoption of UOW.

Conclusion

This research aimed to explore a pressing and emerging urban development trend: the expansion of UOW, employing scientific methods to pursue a human-centered approach to development. Previous research identified a negative psychological link with UOW, but the precise mechanisms remained unclear. This is a theoretical but also practical problem, as architectural and engineering solutions were mostly intuitive and opportunistic. We give solid evidence that a central psychological mechanism that underlies the negative association of UOW is the perception of control. With a human-centered approach in focus, the design of UOW can now target more specific solutions, emphasizing autonomy, personal control, and choice for occupants. Consequently, the scientific insights presented in this paper are not only valuable to the academic community but also hold significance for urban planners, designers, engineers, and policymakers.

Data availability

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

Received: 29 March 2024; Accepted: 6 February 2025
Published online: 28 February 2025

References

1. Nagy, E., Yasunaga, S. & Kose, S. Japanese office employees' psychological reactions to their underground and above-ground offices. *J. Environ. Psychol.* **15**, 123–134 (1995).
2. Lee, E. H., Christopoulos, G. I., Lu, M., Heo, M. Q. & Soh, C.-K. Social aspects of working in underground spaces. *Tunn. Undergr. Space Technol.* **55**, 135–145 (2016).
3. Sarkodie, S. A., Owusu, P. A. & Leirvik, T. Global effect of urban sprawl, industrialization, trade and economic development on carbon dioxide emissions. *Environ. Res. Lett.* **15**, 034049 (2020).
4. Soh, C.-K., Christopoulos, G., Roberts, A. & Lee, E.-H. Human-centered development of underground work spaces. *Proc. Eng.* **165**, 242–250 (2016).
5. Balland, P.-A. et al. Complex economic activities concentrate in large cities. *Nat. Hum. Behav.* **4**, 248–254 (2020).
6. Broere, W. Urban underground space: Solving the problems of today's cities. *Tunn. Undergr. Space Technol.* **55**, 245–248 (2016).
7. Sterling, R. & Nelson, P. City resiliency and underground space use. *Advances in Underground Space Development* 43–55 (2013).
8. Volchko, Y. et al. Subsurface planning: Towards a common understanding of the subsurface as a multifunctional resource. *Land Use Policy* **90**, 104316 (2020).
9. Arshad, S. et al. Quantifying the contribution of diminishing green spaces and urban sprawl to urban heat island effect in a rapidly urbanizing metropolitan city of Pakistan. *Land Use Policy* **113**, 105874 (2022).
10. United Nations. World urbanization prospects: the 2018 revision. (2019).
11. De Mulder, E. F. J., Varn Ree, C. C. D. F. & Hack, H. R. G. K. Chapter 9: Geo-environmental Aspects of European Underground Infrastructure. In *Culshaw, M.G., Osipov, V.I., Booth, S.J. & Victorov, A.S. (Eds), Environmental Security of the European Cross-Border Energy Supply Infrastructure. NATO Science for Peace and Security Series C: Environmental Security.* 133–153 (Springer, Dordrecht, Netherlands, 2015).
12. Passi, A., Nagendra, S. S. & Maiya, M. P. Characteristics of indoor air quality in underground metro stations: A critical review. *Build. Environ.* **198**, 107907 (2021).
13. Yu, J., Kang, Y. & Zhai, Z. J. Advances in research for underground buildings: Energy, thermal comfort and indoor air quality. *Energy and Buildings* **215**, 109916 (2020).
14. Wen, Y., Lau, S.-K., Leng, J. & Liu, K. Sustainable underground environment integrating hybrid ventilation, photovoltaic thermal and ground source heat pump. *Sustain. Cities Soc.* **90**, 104383 (2023).

15. Rossi, E. & Attaianese, E. Research synergies between sustainability and human-centered design: A systematic literature review. *Sustainability* **15**, 12884 (2023).
16. Ringstad, A. J. Perceived danger and the design of underground facilities for public use. *Tunn. Undergr. Space Technol.* **9**, 5–7 (1994).
17. Shao, Y., Fang, Y., Wang, M., Chang, C.-H.D. & Wang, L. Making daily decisions to work from home or to work in the office: The impacts of daily work-and COVID-related stressors on next-day work location. *J. Appl. Psychol.* **106**, 825–838 (2021).
18. Hartig, T., Johansson, G. & Kylin, C. Residence in the social ecology of stress and restoration. *J. Soc. Issues* **59**, 611–636 (2003).
19. Coleman, E., Shealy, T., Grohs, J. & Godwin, A. Design thinking among first-year and senior engineering students: A cross-sectional, national study measuring perceived ability. *J. Eng. Educat.* **109**, 72–87 (2020).
20. Hartig, T., Kylin, C. & Johansson, G. The telework tradeoff: Stress mitigation versus constrained restoration. *Appl. Psychol.* **56**, 231–253 (2007).
21. Lee, E. H., Christopoulos, G. I., Kwok, K. W., Roberts, A. C. & Soh, C.-K. A psychosocial approach to understanding underground spaces. *Front. Psychol.* **8**, 452 (2017).
22. Ahmed, S. H., Taha, D. S. & Hasan, A. E. Evaluating the legibility of complex buildings: A quantitative model for indoor wayfinding. *WIT Trans. Ecol. Environ.* **249**, 139–151 (2020).
23. Hane, T., Muro, K. & Sawada, H. Psychological factors involved in establishing comfortable underground environments. In *Urban Underground Utilization '91. Proceedings of the 4th International Conference on Underground Space and Earth Sheltered Buildings, 3–5 December, Tokyo* 480–492 (1991).
24. Wada, Y. & Sakugawa, H. Psychological effects of working underground. *Tunn. Undergr. Space Technol.* **5**, 33–37 (1990).
25. Lee, E. H. et al. The underground workspaces questionnaire (UWSQ): Investigating public attitudes toward working in underground spaces. *Build. Environ.* **153**, 28–34 (2019).
26. Levenson, H. Distinctions within the concept of internal-external control: Development of a new scale. In *Proceedings of the Annual Convention of the American Psychological Association* vol. 7 261–262 (American Psychological Association, 1972).
27. Rotter, J. B. Generalized expectancies of internal versus external control of reinforcements. *Psychol. Monographs* **80**, 1–28 (1966).
28. Gore, J. S., Griffin, D. P. & McNierney, D. Does internal or external locus of control have a stronger link to mental and physical health?. *Psychol. Stud.* **61**, 181–196 (2016).
29. Kesavayuth, D., Binh Tran, D. & Zikos, V. Locus of control and subjective well-being: panel evidence from Australia. *PLoS One* **17**, e0272714 (2022).
30. Stillman, S. & Velamuri, M. If life throws you lemons try to make lemonade: does locus of control help people cope with unexpected shocks. *Available at SSRN 2835350* (2016).
31. Ahlin, E. M. & Lobo Antunes, M. J. Locus of control orientation: Parents, peers, and place. *J. Youth Adolescence* **44**, 1803–1818 (2015).
32. Xue, S., Kidd, M. P., Le, A. T., Kirk, K. & Martin, N. G. The role of locus of control in adulthood outcomes: Evidence from Australian twins. *J. Econom. Behav. Organiz.* **179**, 566–588 (2020).
33. Twenge, J. M., Zhang, L. & Im, C. It's beyond my control: a cross-temporal meta-analysis of increasing externality in locus of control, 1960–2002. *Pers. Soc. Psychol. Rev.* **8**, 308–319 (2004).
34. McElroy, J. C., Morrow, P. C. & Ackerman, R. J. Personality and interior office design: Exploring the accuracy of visitor attributions. *J. Appl. Psychol.* **68**, 541 (1983).
35. Hellwig, R. T. Perceived control in indoor environments: a conceptual approach. *Build. Res. Inf.* **43**, 302–315 (2015).
36. Tussyadiah, I. P. Factors of satisfaction and intention to use peer-to-peer accommodation. *Int. J. Hosp. Manag.* **55**, 70–80 (2016).
37. Levenson, H. Differentiating among internality, powerful others, and chance. In *Research with the locus of control construct* vol. 1 15–63 (Academic Press, New York, 1981).
38. Land Transport Authority. Motor Vehicle Population by Vehicle Type. (2020).
39. Xie, X., Wang, R., Gou, Z. & Chen, S. A comparative study of gender differences in healthy office building strategies. *Front. Psychol.* **14**, 1146260 (2023).
40. Khaleghimoghaddam, N. A neurological examination of gender differences in architectural perception. *Archit. Sci. Rev.* **67**, 281–290 (2024).
41. Zhang, Y., Wu, Z., Wu, Z., Liu, Y. & Yang, Z. Using Space Syntax in close interaction analysis between the elderly: Towards a healthier urban environment. *Buildings* **13**, 1456 (2023).
42. Levenson, H. Multidimensional locus of control in psychiatric patients. *J. Consul. Clin. Psychol.* **41**, 397–404 (1973).
43. Hayes, A. F. *Introduction to Mediation, Moderation, and Conditional Process Analysis: A Regression-Based Approach* (Guilfod Press, 2022).
44. Lachman, M. E. & Weaver, S. L. The sense of control as a moderator of social class differences in health and well-being. *J. Personal. Soc. Psychol.* **74**, 763–773 (1998).
45. Su, Y. et al. White-and Blue-collar workers responses' towards underground workspaces. *Tunn. Undergr. Space Technol.* **105**, 103526 (2020).
46. Galvin, B. M., Randel, A. E., Collins, B. J. & Johnson, R. E. Changing the focus of locus (of control): A targeted review of the locus of control literature and agenda for future research. *J. Organiz. Behav.* **39**, 820–833 (2018).
47. Szopinska-Mularz, M. & Lehmann, S. Urban farming in inner-city multi-storey car-parking structures-adaptive reuse potential. *Future Cities Environ.* **5**, 4–4 (2019).
48. Choi, J. Developing gardens in urban idle space. *J. Convergence Cult. Technol.* **7**, 327–335 (2021).
49. Dong, X. et al. Effect of thermal, acoustic, and lighting environment in underground space on human comfort and work efficiency: A review. *Sci. Total Environ.* **786**, 147537 (2021).
50. Kim, J., Cha, S. H., Koo, C. & Tang, S. The effects of indoor plants and artificial windows in an underground environment. *Build. Environ.* **138**, 53–62 (2018).
51. Tan, Z. et al. Transitional areas affect perception of workspaces and employee well-being: A study of underground and above-ground workspaces. *Build. Environ.*, 106840 (2020).
52. Yap, H. S. et al. The importance of air quality for underground spaces: An international survey of public attitudes. *Indoor Air* **31**, 2239–2251 (2021).

Acknowledgements

This research is supported in part by the Singapore Ministry of National Development and the National Research Foundation, Prime Minister's Office under the Land and Liveability National Innovation Challenge (L2 NIC) Research Programme (L2 NIC Award No. L2NICCFP1-2013-2). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not reflect the views of the Singapore Ministry of National Development and National Research Foundation, Prime Minister's Office, Singapore.

Author contributions

In this collaborative effort, E.H.L., as the first author, played a role in the development and execution of the study

by leading the conceptualization, conducting the formal analysis and investigation, devising the methodology, and writing the original draft of the manuscript. A.C.R. contributed through his involvement in the investigation and formal analysis, as well as through his critical review and editing of the manuscript. K.W.K. contributions were multifaceted, including conducting investigations, providing resources, contributing to the methodology, and offering supervision to ensure the study's success. J.C. and C.K.S both played roles in refining the manuscript through their review and editing, with C.K.S. also managing the project's administration, acquiring funding, and providing supervision. G.C., the corresponding author, enhanced the study by contributing to the visualization and methodology, managing project administration, acquiring funding, offering supervision, editing and reviewing the manuscript. Together, their combined efforts and unique contributions have shaped this research project.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to G.C.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.