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Underground workspaces: a human factors approach

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Abstract. With increasing population density in urban areas, underground space use in these urban centres is also on the rise. This can be in the form of more traditional underground (UG) facilities, such as water treatment plants and subway stations, but also more diversified uses such as underground offices and data centres. As these relatively novel underground workspaces are constructed, we need to take a human centric approach to ensure that the workers are happy and healthy. When designing any space, it is important to consider the relationships between the environmental, architectural characteristics and behavior and wellbeing. This is crucial in underground developments, as the initial cost of developing an underground space is significantly higher (at least in the short term) than aboveground and would have to be offset by a longer building life. Previous studies show negative attitudes towards working underground and hint at possible psychological and health complaints. Major themes include lighting and circadian rhythms, metabolic changes and claustrophobia. However, these studies are over thirty years old and mainly concentrate on self-report measures. To respond to this chal-

lenge, we have systematically examined the relationship between underground spaces and human performance in a 4 year research program. Using mixed methods such as psychophysiological measurements, cognitive tests and interviews, we examine the architectural and engineering choices that could impact or mitigate specific issues related to underground work environment.

Keywords: underground, workspace, human factors, cognition, social, health, architecture, psychology.

1 Tapping (Hidden Potential of) the Underground

1.1 Overcrowding and the need for land space

The population in cities is rising as more people move to urban areas in search of employment. This shift in population densities has increased overcrowding in cities around the world. For example, as of July 2017, population densities (person per square km) of Singapore and Monaco are 8, 274 and 26, 105 respectively [1]. According to the World Economic Forum, the United Nations (UN) estimates that population densities of urban areas are increasing especially in Asia and Africa with Dhaka having the highest population density in the world at 112, 700 [2]. In comparison, London and Paris each has 5, 637 and 3, 668 people per square km [3].

It is projected that by 2030 there would be 150 more cities with a minimum population of 1 million residents, and the number of megacities (cities with more than ten million residents) is also expected to rise from 31 in 2016 to 41 by 2030 [4]. The increase in population densities in urban cities worldwide necessitates the need for more buildings and infrastructures. The increase in residential areas compels nations to evaluate their urban planning and consider alternative areas to house/ shift their workspaces. Sustainable engineering options which consider the interactions of design, environment, economies of scale and social structures is therefore an appealing option and one that nations are keen to explore. To be sustainable, a solution has to be human centric. It has to be a human factors approach exploring the risks and evaluating the benefits of a proposed solution. This is to ensure it meets an integral aspect of sustainable engineering option: that the solutions emerging from these interactions do not shift existing problems to the next generation thereby posing risks for future generations [5].

1.2 Venturing Below the Surface

One of the main concerns with overcrowding of cities is space allocation. Besides concerns about where to house the growing population, countries and cities also explore where to locate key business infrastructures and industries. Some of the key infrastructures that would need to be relocated would be power grids, waste and water treatment plants, and data storage systems. Other considerations on space requirements would stem from the building of residential buildings. While some countries

had considered buildings that housed both commercial and residential structures, others had also considered expanding the periphery of their urban city [6]. Although this provides an interim solution, it fails to address further growth in population. Besides not addressing the problem, it brings about new issues. Economic geographers place importance on the location of an industry and how a place is socially constructed based on the meanings employees attribute to it [7]. Shifting base from a central location in a city to one on the outskirt or further away has implications. The spatial shift has social, emotional, and psychological impacts on the employees as well as the organizations they work for. As such, organizations and city planners should emphasize smooth transitions in the movement and location of services. One option that countries are increasingly exploring is underground spaces. Venturing below the surface could prove beneficial as industries would still be strategically located within the city center. Moving facilities and industries underground (UG) would also mean freeing up land space aboveground (AG). In addition to this, UG buildings consume less energy in the long term [8]. When considering moving industries and facilities UG, governments and city planners need to consider several factors:

- The views people have about UG,
- UG's psychological and health effects on humans,
- Design and aesthetics of the UG and their impact on the people working in these areas and,
- The type of industries and job types that would be more suitable to be housed UG.

We have reviewed elsewhere [9, 10, 11, 12] previous research on UG spaces and the impact of UG workspaces on UG workers. From our review, we identify 3 main categories: social/ attitudes, psychological, and health effects. In the next section, we present a summary of our review of past research.

2 Previous Research

Past research suggests that UG is associated with negative attitudes and behavior [9]. For example, in East Asian traditional folklore consider UG as the area where departed souls are punished [13]. Besides this, UG is often associated with primitive societies and regarded as a place for the impoverished [14]. The darkness of UG could invoke fear and a sense of entrapment [15]. For those who suffer from claustrophobia and anxiety disorders, being UG could cause them to feel that they are unable to breathe as they could regard UG as an area with limited oxygen supply [16]. However, repeat exposure to this perceived threat to their wellbeing could cause some individuals to adapt their fear response e.g., from initial heart rate increases to gradual reduction [17].

Paradoxically, UG is also regarded as a shelter from natural disasters and war, providing a sense of assurance, and safety [18]. Other protective attributes of UG include possibly providing insulation from the cold due to the rocks/ soil structures UG [19]. However, as UG workspaces could trap the existing heat; cooling or ventilating systems need to be installed to ensure optimum temperature in UG [20]. The

fluctuations in thermal comfort levels brought about by low temperatures and temperatures above 17-23°C, could lead to increases in unsafe work behaviors [21]. Though UG workers describe heat as a negative aspect of their work environment, over time UG workers could adapt to their physical work environment and self-regulate their physiological responses such as body temperatures and cardiovascular functions [22, 23]. UG workers could have higher levels of diurnal melatonin variation due to the limited exposure to sunlight. Past research suggests that this variation could serve to enable adaptation in UG workers' sleep wake cycle so that UG workers could fall asleep easily as well as sleep for a longer duration [24].

Besides adapting to UG space, prior experience of UG workspaces could influence perceptions of the space. Workers with no experience working in UG spaces could have negative perceptions. Being new to a space and not being able to navigate through the space could increase stress levels and decrease focus on cues to navigate the space. Though this has been tested in animals, studies involving human participants are lacking [25]. Furthermore, workers who work long hours in UG could have different attitudes towards the space. Those who worked in UG previously could be more willing to work UG [26]. In addition to this, UG workers who are unsatisfied with their work settings could possibly prefer changes within their work environment to moving to an aboveground workspace. Also, UG workers with control over their work environment could be positive about their work settings [27].

Besides control over their environment, stimulation in the work environment appears to be important. UG environment's role in stimulating workers is ambiguous, with past research suggesting it could under stimulate or overstimulate workers thereby inducing hypostress or hyperstress. Both hypostress and hyperstress could possibly increase mental fatigue [28]. Whether a worker is over stimulated or under stimulated depends on individual characteristics and the ability to cope with stress, and workload. For example, varying noise levels in UG workspaces could have an impact on task performance [29]. However this is dependent on the nature of the task [30]. Besides noise, windowless workspaces could lead to a decrease in job satisfaction as workers could feel disconnected from the outside world [31]. This could be acute in small workspaces where movement is restricted [32]. Windowless environments could also affect wayfinding since external landmarks are absent and cannot be used as reference points [16]. This could induce stress and frustration amongst UG workers [33]. When people have no control over their work environment, they experience learned helplessness and low job satisfaction as they have little stimulation and few opportunities to be decision makers [34].

From our review of past research on UG spaces, we identified several areas that were as yet unexplored or not comprehensively investigated. For example, research on UG workers' experiences had relied heavily on self-reports [10]. Moreover, there was no questionnaire to examine the attitudes and perceptions of this unique group: UG workers. In addition to this, past studies on UG workers typically focused on the UG mining community [35, 36]. Most of the research is three decades old. Furthermore, past research explored the effects of working UG in a fragmented manner wherein individual disciplines dwelt on aspects of the UG looking at, for example, air quality, windowless environments, job satisfaction, and task performance [10].

3 Designing Underground Workspaces

3.1 Systematic Multidisciplinary Research Programme

While past research served as a point of reference, a comprehensive research programme is necessary to explore and identify a multitude of factors that possibly influenced and impacted on (office and manual) workers' experiences of working UG. We began our exploration on what impacts (if at all) workers in the UG working environments. Our team explored working in UG spaces from a multidisciplinary, mixed methods approach. Using health, psychological, and social parameters, we explored the impact of working UG on workers in UG spaces and compared the reported outcomes with our measurements recorded from AG workers. Given the shift in UG space usage and countries considering utilizing UG for office and retail spaces, it is important to explore how working in UG spaces might affect (if at all) different groups of workers. In Table 1, we present an outline of the human factors approaches in our multidisciplinary research programme exploring the effects (if at all) of working in UG spaces.

Table 1. A human factors approach to working in underground spaces

Task	Factors being explored	Method	Previous antecedents
Design and conduct large scale survey on social attitudes on the UG workspaces	Identifying factors that influence/ impact on attitudes and behavior towards working UG	Social attitudes survey (N= 1093)	First survey on attitudes to UG. Advanced psychometric measures.
Comparisons of AG and UG workers	Personality traits Attitudes and behaviors Work fatigue Decision making Risk taking History of chronic illnesses Obesity/overweight Dietary and lifestyle habits Environmental measurements	Computerized tests, personality questionnaires, attitudes survey, blood, urine and environmental measurements (N=464)	Not to such a large extent.
Exploring UG work conditions in other countries	Environmental measurements Design aspects of UG space Attitudes and behaviors	Overseas interviews and site visits. Attitudes survey, blood, urine and environmental measurements (N= 191)	There were some studies but their studies were localized and not across countries.
Psychological responses	Locus of control Individual differences Risk perception Space and work fatigue Work environment's effect on task performance	Computerized tests (N=125) Brain recording (EEG) (N=64) Wayfinding (N=56) Virtual reality experiments	Previously done but not to this extent. Underground Human Performance Lab. Custom designed and built to test psychological responses.

Decision making Risk taking Behavioral inhibition Attention during navigation Error monitoring and psychological responses Virtual reality versus physical settings.	Virtual reality to replicate room setting in UG is a relatively novel approach. Enables observation of psychological responses to changes in room settings in simulations of the real world in a virtual space.

3.2 Insights

In this paper, we present a summary of our research programme exploring the psychological, social, and health effects of working in UG spaces. In addition to this, we explored the effects of the design of UG workspaces on workers' experiences of their physical working environment. We then examined gender and individual differences in perceptions of working in UG. We conducted a large scale social survey on attitudes towards UG. We examined negative association and attitude; and perceptions of security and positive attitude towards UG. Negative associations of UG influence the attitudes people have of UG. Perceptions of security influence positive attitudes towards UG. This suggests a need for more information and promotion of UG spaces as safe areas. We also examined locus of control exploring internal beliefs people had about UG and the extent to which people felt these beliefs were not within their control but up to chance.

Besides beliefs, we also explored risk taking and decision making behaviors as well as psychological responses to error monitoring and compared the responses of our AG and UG participants to observe any impact caused by differences in physical working environments. We then investigated lifestyles, physical activity, environmental measurements, and history of chronic illnesses amongst participants working in AG and UG. We extended our studies from a Singaporean population to UG workers in four Chinese cities, a facility in North America, and UG workspaces in Norway and Sweden. We looked at the design and aesthetics of these places and UG workers' perceptions of these spaces. We then looked beyond UG workspaces and considered transitional areas leading to or from UG workspaces. We looked at the design and aesthetics of these places and people's perceptions of these spaces.

4 Conclusion

The level of security attributed to a UG workspace impacts on how positive a person feels about UG. Similarly, the physical dimensions and aesthetics of a transitional space, linking a UG space to an AG space plays a part in how confined a person feels being in UG space. UG workers with differing responsibilities could perceive UG workspaces differently. However, being in a UG space for a length of time influences how one adapts to this space. This may possibly negate initial feelings of negativity towards the space. In conclusion, it is important to consider space and aesthetics when

designing UG workspaces. It appears that there is very little difference between AG and UG workspaces once workers have acclimatized to their UG settings. However, more research needs to be conducted to explore these findings in depth.

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