Review of the potential health effects of light and environmental exposures in underground workplaces

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Title: Review of the potential health effects of light and environmental exposures in underground workplaces

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Highlights

- Studies investigating health effects of underground workplaces are limited.
- Several studies reported adverse health effects but overall findings were inconclusive.
- Experimental studies are needed to better understand the impact of underground spaces on health.

Abstract

Underground workplaces are an important element in modern urban planning. As a result, an increasing but unquantified proportion of the population is being regularly exposed to them. We narratively reviewed the literature on the range of possible environmental exposures, and the possible health effects, to identify future research directions. There is a large but mainly observational research literature on likely underground exposures, including effects of artificial lighting, shift working and light at night on circadian disruptions and associated health effects. There are five studies comparing underground and aboveground environments. Insufficient sleep leading to circadian disruption is one physiologic pathway, but there is increasing evidence that artificial lighting also causes circadian disruptions. Working underground may increase exposure to these risks, and may also be associated with vitamin D deficiency, sick building syndrome, excessive noise, radon exposure, and negative psychological effects. In order to plan appropriate interventions, we need to expand our knowledge of the health effects of underground environments. Larger and longer-term studies are required to measure a range of human factors, environmental exposures and confounders. Controlled trials with health economic analyses of new lighting technologies are also required.

Keywords: Underground workplaces; Health effects; Indoor environments; Review.

1 Introduction

Utilisation of underground (UG) spaces for various purposes has been a part of human civilization since it first evolved (Kaliampakos, Benardos et al. 2016, Li, Xu et al. 2016). However, it is only during the last few decades that UG spaces have become a common feature of planning and development in many cities (Bobylev 2016, Doyle 2016). UG spaces have proven to be an effective solution for tackling pressing issues such as land shortage due to rapid population growth, increasing urbanisation, and environmental impacts of urban traffic (Sterling, Admiraal et al. 2012, Romanova 2016, Tengborg and Sturk 2016, Wallace and Ng 2016). Thus, many countries such as Sweden, Norway, Netherlands, Japan, US, Hong Kong, the United Kingdom, Turkey, Poland, Canada, Singapore and China have made UG space development part of their policy agenda (Sterling, Admiraal et al. 2012, Broere 2016, Kishii 2016, Qihu 2016, Tengborg and Sturk 2016, Vähäaho 2016, Wallace and Ng 2016, Zhao, Peng et al. 2016, Zhou and Zhao 2016, Shan, Hwang et al. 2017). However it is challenging to obtain an estimate of the size of the global population which currently works UG, although it must number in the millions (Bobylev 2016). About a million people reside in the network of bomb shelters under Beijing alone (Kim 2016).

UG spaces may have environmental, social and economic benefits such as reduced air pollution and external noise, greater safety, reduced crowding, and saving of energy and natural resources (Asociación Española de Túneles y Obras 1996, Sellberg 1996, Bhalla, Yang et al. 2005, Sterling, Admiraal et al. 2012, Lee, Christopoulos et al. 2017, Shan, Hwang et al. 2017). Risks of working in UG spaces include the limited or lack of exposure of natural sunlight and sounds from the outside world (Carmody and Sterling 1987, Carmody and Sterling 1990, Küller and Wetterberg 1996, Lee, Christopoulos et al. 2017). To date, researchers have mostly focused on the engineering, and immediate physiological and psychological aspects of the UG working

environments, (Carmody and Sterling 1987, Carmody and Sterling 1993, Nagy, Yasunaga et al. 1995, Lee, Christopoulos et al. 2016, Roberts, Christopoulos et al. 2016, Lee, Christopoulos et al. 2017) and very few have studied the long term health effects (Küller and Wetterberg 1996, Aries, Veitch et al. 2010, Soh, Christopoulos et al. 2016). Some of the latter research has demonstrated that UG spaces appear to be less desirable to workers as they may be associated with darkness (the absence of daylight), coldness, dampness (mould and fungal growth), poor air quality due to insufficient ventilation or fear of confinement as well as other safety concerns (Wada and Sakugawa 1990, Küller and Wetterberg 1996, Soh, Christopoulos et al. 2016, Lee, Christopoulos et al. 2017). These disadvantages might in addition constitute risk factors for adverse health outcomes, and as a result in reduced productivity (Manav 2007, Aries, Veitch et al. 2010, Lowe, Boulange et al. 2014). Therefore, it is crucial to investigate the potential risks as well as benefits of UG workplaces considering epidemiology, economics, environmental and occupational safety.

Aries et al. reported that in windowless aboveground (AG) workplaces, various factors such as lighting quality, cleanliness and external access are closely related to comfort, stress levels, health-related and psychological well-being, and sleep quality (Aries, Veitch et al. 2010). Moreover, there may be other shortcomings in the UG environment such as high humidity, mould and fungal growth, poor air quality due to insufficient ventilation, and the absence of daylight (Küller and Wetterberg 1996, Ree Joo and Choi 1998). Shan et al. administered a questionnaire to 30 Singapore-based construction companies involved in UG projects and reported that limited access to natural light was regarded as the greatest disadvantage (Shan, Hwang et al. 2017).

Despite the rapidly increasing usage of UG space internationally, there is an evidence gap in their potential health effects that needs to be filled. This paper aims to narratively review and summarize the possible environmental exposures and plausible health effects of UG spaces.

2 Methods

In this review we have attempted to answer the question: what are the known or possible health effects of UG workplaces? Because of the wide range of exposures involved it was not feasible to conduct a single systematic review. We carried out this narrative review using the following search terms “underground spaces”, “subsurface space”, “subterranean workplaces”, “working underground”, together with “health impact”, “health implications”, “underground and health”, and as well as terms such as “circadian disturbances”, “light exposure”, “vitamin D”, “indoor air quality”, “environmental parameters”, “particular matters”, “volatile organic compounds”, “sick building syndrome (SBS)”, “mental health” “sleep patterns”, and “underground and aboveground spaces”. The searches were performed through PubMed, Medline (Ovid), Embase (Ovid), Science Direct, Scopus, Google Scholar, and through websites including the Associated Research Centers for the Urban Underground Space (ACUUS), the World Health Organisation (WHO), United Nations and various government websites including some environment ministries since 1980 to 2017. Both animal and human studies were eligible. Any types of evidence (including grey literature) published papers, official reports or documents discussing UG workplaces were included. As this was not a systematic but narrative review, no formal validity/quality, risk of bias assessments were done; and no exclusion criteria were applied. A descriptive analysis was carried out based on two key themes: potential health effects due to: 1) the limited light exposure (including: a. health effects of circadian disruptions; b. shift working; c. light at night; d. light wavelengths on circadian rhythms; e. vitamin D deficiency), and 2) other environmental exposures (including: a. indoor air quality and sick building syndrome; b. excessive noise; c. radon). Finally, we compared studies of actual health effects of AG and UG working.

3 Results

As our focus is on UG workplaces, we first discuss the very limited evidence base comparing UG and AG environments. As lighting and sunlight exposure is an evident difference between UG and most AG spaces (Lee, Christopoulos et al. 2017), we then report the major known effects of light on health through circadian rhythm disruption and effects on sleep quality and mental health, as well as vitamin D deficiency as health consequences of lack of sunlight, or an appropriate artificial alternative. We also discuss air pollution exposures. Please see **Figure 1** for the overview of the possible health effects associated with working in underground spaces. **Table 1.** Summarizes the potential (or actual) health effects of working in underground spaces with mechanisms of action involved and suggested explanations.

Circadian disruptions

A characteristic of UG workplaces is exposure to artificial electric lighting rather than sunlight. Regular exposure to adequate sunlight (or similar artificial light), and day-night contrasts, are important for human health and wellbeing (Bonmati-Carrion, Arguelles-Prieto et al. 2014, Martinez-Nicolas, Madrid et al. 2014). These exposures are mediated by the suprachiasmatic nucleus (SCN), a brain area which acts as central pacemaker for the human circadian system (Brown 1994, Arendt 2006, Czeisler and Gooley 2007, Brainard and Hanifin 2014, Kuehn 2017). In response to changes in gene expression driven by the light-dark cycle, the SCN also stimulates the release of cortisol that triggers waking, and melatonin (MLT), which signals when it is time for sleep. Serotonin is normally prevalent during the day, and undergoes conversion to MLT during night. Sunlight or bright light has a positive effect on the serotonin system (Lambert, Reid et al.). An increase in serotonin in the brain is positively correlated with a focused mental outlook and happiness while a low level aggravates sadness (Ehrine J.P. Manzana 2001, Young 2007). More recently, researchers have discovered that peripheral organs and tissues have separate

circadian rhythms or “clocks” that are controlled by the cyclic expression of clock genes in their cells (Bray and Young 2009, Challet 2015, Husse, Eichele et al. 2015).

Many studies have documented associations between circadian disruptions and metabolic diseases or various cancers (Evans and Davidson 2013). Disruptions have also been shown to be associated with an increased risk of mood, psychiatric and neurodegenerative disorders (Driesen, Jansen et al. 2010, Wulff, Gatti et al. 2010). Recent research in cells, rodents, and humans suggests that the health consequences of circadian disruption may be substantial (Buxton, Cain et al. 2012, Stevens, Brainard et al. 2014). For example, light at night (LAN) markedly increases the growth of human breast cancer xenografts in rats. Recent evidence from basic biomedical studies has sparked further interest in the involvement of daily rhythms and their disruption in the development of obesity and Type 2 diabetes (T2D) (Kalsbeek, la Fleur et al. 2014). Here peripheral molecular clocks, which govern rhythmicity in particular organs, appear to be involved. Current evidence supports a role for pancreatic clock genes in the development of T2D via their role in insulin release, and for liver clock genes in the control of glucose tolerance through their effect on hepatic gluconeogenesis, although it also appears that MLT acts independently on glucose homeostasis (Owino, Contreras-Alcantara et al. 2016). A recent review describes these pathways in more detail, with a view to improving therapeutic options (Smolensky, Hermida et al. 2016).

MLT and circadian disruption are associated with a range of mood and psychiatric disorders including schizophrenia, seasonal affective disorder, non-seasonal depressive disorder and bipolar disorder (Pacchierotti, Iapichino et al. 2001, Ciarleglio, Resuehr et al. 2011, Karatsoreos 2014). It has also been reported that morning sunlight reduced the length of hospitalization in bipolar depression (Benedetti, Colombo et al. 2001, Benedetti and Dallaspesza 2009). Thus realignment of the sleep-wake cycle can assist mood-stabilization (McClung, Ciarleglio, Resuehr et al. 2011,

McClung 2011), and properly timed exposure to sunlight may have an impact on mental health (Mead 2008, Hahn, Grynderup et al. 2011).

Shift working

About 20% of the working population in developed countries work some late or nightshifts. Shift working, like working UG, involves increased exposure to artificial lighting and decreased exposure to sunlight, and so could be seen as a paradigm for UG workspaces, while taking into account sleep loss, which is common in shift workers. Epidemiologic research on shift working has converged with biological research to demonstrate effects on human health. A systematic review (SR) of studies linking shift work with metabolic risk factors found 39 articles describing 22 studies (Proper, van de Langenberg et al. 2016). Strong evidence was found for a relation between shift work and increased body weight/body mass index (BMI), risk of overweight, and impaired glucose tolerance. Recent meta-analyses and SRs conclude that shift work increases the risk for developing T2D (Gan, Yang et al. 2014, Anothaisintawee, Reutrakul et al. 2016). An SR and meta-analysis of 34 studies in over two million people found, after adjustment, shift work was associated with coronary heart disease (CHD) (risk ratio 1.24, 1.10 to 1.39) and stroke (1.05, 1.01 to 1.09; $p < 0.001$) (Vyas, Garg et al. 2012). A prospective cohort study of CHD incidence in 189,158 workers in the Nurses' Health Studies (NHSs) found that in NHS1 the hazard ratio (HR) of less than 5 years of rotating night shift work was 1.02 (95% CI, 0.97-1.08), for 5 to 9 years 1.12 (95% CI 1.02-1.22) and for 10 years or more 1.18 (95% CI, 1.10-1.26), $p < 0.001$ for trend (Vetter, Devore et al. 2016). In NHS2, the HRs were 1.05, 1.12 and 1.15 respectively. A meta-analysis of the dose-response relationship between shift work and female breast cancer showed that every 5-year increase of exposure to night shift work raises the risk of breast cancer by 3% (pooled RR = 1.03, 95% CI 1.01–1.05; p for heterogeneity < 0.001) (Wang, Yeung et al.

2013), but a similar study showed no association. A population-based case-control study of 3,137 males with incident cancer at one of 11 anatomic sites found significant associations in men between ever working at night and cancer risk in several sites (Parent, El-Zein et al. 2012, Vyas, Garg et al. 2012).

Conversely, another characteristic of shift working is the need to sleep during daylight hours, which may result in insufficient sleep overall. The relations of shift work to cardiometabolic diseases mimic those with insufficient sleep. Laboratory studies indicate that cardiometabolic stress and at least short-term decline in cognitive functions are increased by shift work, as well as by sleep loss. Kecklund et al suggest that, as the health consequences of shift work and insufficient sleep are very similar, they are likely to share the common mechanism of circadian disruption (Kecklund and Axelsson 2016). This suggests that there may not necessarily be a causal relationship between exposure to artificial light and adverse health outcomes, rather that the health effects of shift working are a product of sleep loss and the resulting circadian disruption. Of course, shift working may also occur in UG workplaces.

Light at night (LAN)

Any consideration of the health effects of light in UG workplaces needs to take into account light in the home environment of workers. There is now a hypothesis linking LAN and increased disease risks, which postulates a linkage through MLT. Most indolamines like MLT can act as scavengers of oxygen radicals, which damage DNA, and DNA damage can cause cancer (Stevens 2009). There is growing epidemiologic evidence of an association between LAN and cancer risk (Stevens and Rea 2001, Haim and Portnov 2013, Hurley, Goldberg et al. 2014, Stevens, Brainard et al. 2014, Haim and Zubida 2015, Kim, Lee et al. 2015). An SR of the dose response relationship of artificial LAN exposure and risk for breast cancer found a risk ratio (RR) of 1.17,

95% CI: 1.11-1.23) for high LAN (Yang, Deng et al. 2014). However a study using data from the NHS2 cohort observed an association between residential outdoor LAN and breast cancer incidence, but only in past and current smokers (HR=1.10 95% CIs 1.01, 1.19) (James, Bertrand et al. 2017). On the other hand, it might be dim light during the day that leads to a reduction of nocturnal MLT levels, as bright daytime light augments MLT secretion the following night (Kantermann and Roenneberg 2009). Also it is not LAN by external time but by internal time that is relevant for MLT suppression, which is defined by the clock's phase of entrainment, and which shows large inter-individual differences (chronotypes). Nevertheless the health effects of LAN has been the subject of policy statements and considerable media coverage (American Medical Association 2012).

Light wavelengths on circadian rhythms

In the comparative studies above neither Küller and Wetterberg nor Leger et al measured wavelengths of light, only light intensity (illuminance). It has only recently become clear that different wavelengths have different effects on human circadian rhythmicity (Stevens, Brainard et al. 2014). Circadian phase resetting and MLT suppression in response to bright monochromatic light is most sensitive to short-wavelength (blue) light, indicating that melanopsin has a primary role in human circadian photoreception (Czeisler and Gooley 2007). Exposure to light sources at night containing blue light (high-intensity discharge and fluorescent lamps have blue emissions) may pose a health risk. Evening use of blue light-emitting devices negatively affects sleep and circadian timing (Benke and Benke 2013). In adolescents, compared with clear lenses, blue-blocker glasses significantly attenuated LED screen-induced MLT suppression in the evening and decreased vigilant attention and subjective alertness before bedtime (Van Der Lely, Frey et al. 2015). In human experiments even very dim (0.1 lux) blue light suppresses MLT more than other colours. Monochromatic red light at 100 lux, a reasonable living room lighting level, would take

403 hours of exposure to suppress MLT by 50%; a candle, 66 minutes; a 60 watt incandescent bulb 39 minutes; a 58 watt fluorescent light 15 minutes; while a pure white high-output LED- which emits a lot of blue light – takes only 13 minutes (Pauley 2004). Nighttime lighting should be dim, eliminate wavelengths in the blue, and employ lights with wavelengths shifted toward the yellow and orange (Bonmati-Carrion, Arguelles-Prieto et al. 2014). Conversely, there is evidence that blue light in the daytime, especially morning, is effective in preventing MLT suppression at night (Holzman 2010, Gabel, Maire et al. 2013). This evidence has appeared just as LEDs are replacing incandescent halogen lamps on energy efficiency grounds. New lighting technologies which replicate the spectrum of sunlight are becoming available (Jou, Kumar et al. 2015, Jou, Yu et al. 2017, SORAA Inc 2017), but they are still very expensive and, because their health impact is unknown, should be subject to randomised controlled trials (RCTs), including health economic analyses.

Vitamin D deficiency

Vitamin D is a hormone essential for a number of functions in the body including calcium absorption, cell proliferation and differentiation, and regulation of immuno- and neuromuscular system (Aranow 2011, Wintermeyer, Ihle et al. 2016). The skin is the major site for synthesis of vitamin D, where ultraviolet rays from sunlight penetrate into the epidermis and activate the cycle of reactions triggering the production of Vitamin D. Vitamin D levels in the skin are affected by many factors including pigmentation, age, season and kidney function (Spiro and Buttriss 2014).

According to the 2011 clinical practice guidelines recommended by the US Endocrine Society (Holick, Binkley et al. 2011), the levels of plasma 25(OH)D concentrations required for broader health benefits are categorized as optimal (≥ 30 ng/mL), insufficient (21–29 ng/mL; 525-725 nmol/liter), and deficient (< 20 ng/mL; 50 nmol/liter) (Man, Li et al. 2017). South East Asian

studies suggest high levels of vitamin D deficiency (Smith, Wimalawansa et al. , van der Rhee, Coebergh et al. 2009, Nimitphong and Holick 2013, Sharifi, Mousavinasab et al. 2013, Baggerly, Cuomo et al. 2015, Bi, Tey et al. 2016). Likely reasons could be genetics, pigmentation, cultural factors (Tan, Saw et al. 2013, Neo and Kong 2016, Man, Li et al. 2017), lifestyle changes, frequent usage of sunscreen, or inadequate dietary intake (Tan, Saw et al. 2013, Neo and Kong 2016). Working UG could in theory, contribute to an increase in vitamin D deficiency. Space flight, coupled with space crews' decreased dietary intake of vitamin D, has been associated with a reduction in body stores of vitamin D (Smith, Abrams et al. 2014). However, in two earthbound studies, there was no significant difference in 25(OH)D levels between AG and UG workers (Shuster, Chadwick et al. 1982, S Sarikaya 2006).

In addition to long-established outcomes such as osteomalacia, osteoporosis and rickets, and in accordance with its involvement in neurological functioning, low levels of vitamin D have been found to be associated with dementia, Alzheimer's disease (Llewellyn, Lang et al. 2011, Annweiler, Rolland et al. 2012, Banerjee, Khemka et al. 2015), multi-morbidity (Meems, de Borst et al. 2015), insulin resistance and T2D, low-grade inflammation and inflammatory bowel disease (Holick 2007, Baggerly, Cuomo et al. 2015, Wamberg, Pedersen et al. 2015, Bi, Tey et al. 2016). In a review of all published case-control and cohort studies concerning cancers, sunlight and vitamin D, chronic sun exposure was associated with a reduced risk of colorectal, breast, and prostate cancer and lymphoma. On the other hand, a Cochrane review including 50,623 participants concluded that any possible intervention effect is lower than 5% cancer relative risk reduction (Bjelakovic, Gluud et al. 2014). However both these reviews indicated a high risk of attrition bias and type 1 error in included studies.

The most thorough review to date is an overview of 107 SRs and 74 meta-analyses of observational studies of vitamin D concentrations, and 87 meta-analyses of RCTs of vitamin D

supplementation (Theodoratou, Tzoulaki et al. 2014). Associations between vitamin D and 137 outcomes were explored. Overall, 30 (63%) of the 48 meta-analyses of observational studies, and 13 (23%) of the 57 meta-analyses of RCTs, reported a nominally statistically significant summary result. The authors concluded that highly convincing evidence of a clear role of vitamin D does not exist for any outcome, but associations with a selection of outcomes are probable. Given the uncertainty of the evidence base, the current cut-off levels for prevalence of Vitamin D deficiency may need to be revisited (Holick and Chen 2008) and the long-term effects of UG workspaces on vitamin D levels need to be studied further.

Indoor air quality and sick building syndrome (SBS)

In developed countries most people spend most of their lives in indoors, so the impact of indoor environmental parameters are very important (Ooi, Goh et al. 1998, Sahlberg, Gunnbjörnsdottir et al. 2013). Due to inadequate ventilation systems and influx of outdoor pollutants, many hazardous components can remain in indoor air such as gaseous pollutants (SO₂, NO_x, CO, ozone), volatile organic compounds (VOCs), biological threats, pesticides, radon and particulate matter, all of which may increase the susceptibility to respiratory disease, cardiovascular diseases (CVD) and cancers (WHO 1988, Sahlberg, Gunnbjörnsdottir et al. 2013, Jung, Liang et al. 2014). The UG environment may also have an effect on indoor air quality, as UG spaces tend to have higher air temperature and humidity than AG (Shan, Hwang et al. 2017).

Sick building syndrome (SBS) is a recognized health effect of indoor environments (Andersson and Stridh 1986, WHO 1988, World Health Organization Regional Office for Europe Copenhagen 1990, Olesen 2014, Grainne, Lukumon et al. 2015). SBS is defined as an excess of work-related irritations of the skin and mucous membranes as well as other symptoms, including headache, fatigue, and difficulty concentrating, reported by workers in modern office buildings

(Ooi, Goh et al. 1998, Olesen 2014, Olesen 2014). Humidity and temperature are correlated with SBS (McGill, Oyedele et al. 2015). High humidity promotes bacterial and fungal growth (Carmody and Sterling 1987) and microbial air pollution may lead to SBS and respiratory health problems (McGill, Oyedele et al. 2015). A meta-analysis of 33 studies reported associations between mould and dampness and the development of upper respiratory tract symptoms (odds ratio [OR] 1.7), cough (OR 1.67), wheeze (OR 1.5), current asthma (OR 1.56), and ever-diagnosis of asthma (OR 1.37) (Fisk, Eliseeva et al. 2010). Other indoor pollutants such as VOCs, particulate matter (PM₁ & PM_{2.5}), carbon monoxide (CO), and carbon dioxide (CO₂) also have proven to be risk factors for SBS (Mandal and Brandl 2011). However a study in Singapore confirmed stress to be a significant and independent determinant of SBS symptoms (Ooi and Goh 1997).

Excessive noise

In a work environment, noise can be caused by occupational or environmental factors. Occupational noise refers to workplace-specific noise generated by machines, telephones and conversations, and environmental noise includes external traffic, industrial activity and public works (NIOSH 1998, Schomer 2005, Hansell, Blangiardo et al. 2013). Building UG spaces could be a protective factor, because environmental noise levels can be reduced (Durmisevic 1999, Godard 2004, Broere 2016). However, in some studies, higher levels of noise were reported in UG environments, because of mechanical installations for artificial ventilation (Küller and Wetterberg 1996). Although the UG environment may be protected from environmental noise, it may also be affected by heightened occupational noise e.g. in UG train stations (Kang 1997). Environmental and occupational noise exposure can induce hearing impairment, sleep disturbance, hypertension and CVD (Passchier-Vermeer and Passchier 2000, Stansfeld and Matheson 2003, Hansell, Blangiardo et al. 2013, Jenny Selander 2013, de Souza, Périssé et al.

2015). A better understanding of noise exposure-response relationships is required in UG environments, by measuring noise alongside other exposures.

Radon

UG facilities may lead to increased radon exposures. Radon is an odourless and invisible, naturally-occurring radioactive gas which can permeate surrounding soil and rocks and enter buildings through cracks or gaps in the floors and walls. Radon and its decay products (known as radon “daughters” or “progeny”) emit highly ionizing alpha-radiation. Radon concentration is low AG due to dilution, however there is a significant level in UG structures, and highest levels UG spaces in contact with the soil such as mines, caves and water treatment facilities (Anastasiou, Tsertos et al. 2003, WHO 2009). Radon exposure can be prevented or reduced by proper sealing, depressurization systems, extraction pipework and positive ventilation for existing buildings, and installing radon-proof barrier/membranes within the floor structure, provision of a ventilated sub-floor void, or a radon sump for new buildings.

There is no agreement about the safe level of radon, which varies widely across countries. In the US, modifying homes with radon levels at or above 4 picocuries per liter of air (pCi/L) (148 Bq/m³)(EPA 2013) is recommended, whereas in UK and Canada, the action level for residences is 200 Bq/m³ (5.41 pCi/l) and for workplaces is 400 Bq/m³ (10.82 pCi/l) (Canadian Center for Occupational Health and Safety , Health and Safety Executive). In China, the safety level set for radon and its daughters is 100 Bq /m³ for newly-built rooms, 200 Bq/m³ for buildings constructed after 1979, and 400 Bq/m³ for buildings constructed before 1979, or not meeting the public standard (Xiaoyan, Baoshan et al. 2005). In 2009, WHO recommended that governments should adopt the reference level of 100 Bq/m³ (WHO 2009).

However, even at the recommended level radon exposure may still carry a risk. Radon is an independent risk factor for lung cancer, and there is a dose-response relationship. In a review of 11 longitudinal studies among miners, there was a linear association between radon exposure and lung cancer (WHO 2009). Risk increased by 16% per 100 Bq /m³ increase in long term average radon concentration (WHO 2009). In a US study adult women with a 15-year exposure at an average radon exposure of 4 pCi/liter had a 24% to 83% increased risk of lung cancer (Field, Steck et al. 2000). Consistent with this finding, in a study in Gansu Province, China, there was a 14% increased risk of lung cancer at the average radon exposure of 100 Bq/m³ (Wang, Lubin et al. 2002). In contrast, a study in the Shenyang area of China did not find an association, but this was a study of homes (Blot, Xu et al. 1990). This may be due to low lifetime radon background exposure in the latter. In a case-control study amongst uranium miners, a positive association between radon exposure and leukemia has been reported (Kulich, Rericha et al. 2007). There is no concrete evidence of effects of radon on other diseases such as CVD (Xuan, Lubin et al. 1993, Tomasek, Darby et al. 1994, Keller, Kappel et al. 1996, Villeneuve and Morrison 1997, Villeneuve, Lane et al. 2007) and stomach cancer (Auvinen, Salonen et al. 2005). Radon levels vary between seasons and locations. Radon levels in UG buildings should be regularly monitored in case an intervention is required.

Comparative studies of health effects of AG and UG working (including windowless environments)

Our searches revealed only five studies (Küller and Wetterberg 1996, Leger, Bayon et al. 2011), (Xueyuan and Yu 1988, Wada and Sakugawa 1990, Ree Joo and Choi 1998) comparing objective health effects in people in modern-day UG working environments and those working in AG spaces, and one of windowed vs windowless environments (Boubekri, Cheung et al. 2014). They measured different components of circadian rhythm disruption and employed very different

experimental methods. In 1996, Küller and Wetterberg reported that people working in Swedish UG environments (n=75) had lower variation in morning cortisol, lower afternoon levels of cortisol and larger diurnal variation of MLT than people working in AG military installations (n=57) (Küller and Wetterberg 1996). However, no corresponding increase in morning MLT level was observed. The gap between morning and afternoon MLT levels also did not correspond to lighting levels. Despite having lower lighting levels UG, persons working UG had a larger difference between morning and afternoon values of MLT than those working AG. In a South Korean study of 130 employees, UG office workers reported higher rates of dry, itching tired or irritated eyes, sore or dry throat, chest tightness, and dry or itchy skin symptom than AG workers (Ree Joo and Choi 1998). The authors suggested that these may be due to inadequate ventilation. In an experimental study in China, investigators found that subjects working in an UG environment with an increased CO₂ concentration felt dizzier and tired, and had more headaches, lapses of memory and decreased working efficiency compared to the AG group (Xueyuan and Yu 1988). Another study in Japan which investigated fatigue showed that recovery was 40 minutes longer after working in an UG environment compared to AG work (Wada and Sakugawa 1990). However, the authors suggested that these symptoms were more related to poor ventilation rather than the UG location. In 2011, Leger et al. measured subjective reports of sleep quality and disorders in 13,296 UG and AG workers in a single transportation company. Several objective measurements of UG light levels were also made to represent the average light exposure of workers (Leger, Bayon et al. 2011). UG workers reported significantly higher levels of insomnia, sleep problems, somnolence, and feeling sleep deprived compared to AG workers. Both shift and non-shift UG workers had significantly more insomnia and hypersomnia compared to shift workers who worked AG. While the authors did not explicitly conclude or attribute the sleep issues to circadian rhythm disruption, they suggest natural light under-exposure at work may significantly impair sleep in non-light-exposed workers.

Boubekri et al studied 49 participants, of whom 27 worked in windowless environments (Boubekri, Cheung et al. 2014). There were no light measurements. Workers in the windowless environments reported poorer scores on two 36-Item Short Form Health Survey (SF-36) dimensions—role limitation due to physical problems and vitality—as well as poorer overall sleep quality from the Pittsburgh Sleep Quality Index (PSQI) score. Compared to the group without windows, workers with windows had more light exposure during the workweek, a trend toward more physical activity, and longer objective sleep duration.

4 Discussion

Globally the number of people working UG spaces is increasing and therefore identifying the populations at risk and quantifying any specific health effects should be a priority. In this review, we have discussed some of the hypothetical wide-ranging health impacts of UG environments. This included the lack of exposure to daylight in UG environments potentially causing vitamin D deficiency leading to reduced bone mineral density, dementia, Alzheimer's disease, inflammatory bowel disease or type II diabetes. Other environmental exposures such as sick building syndrome (applicable to AG working environments too) also involving poor air quality, noise pollution and radon may cause respiratory or cardiovascular diseases, headaches, fatigue, decreased working efficiency, hearing impairment, sleep disturbance or poor mental health. Those adverse outcomes are known to result from poor ventilation systems, radon, volatile organic compounds, pesticides, and particulate matter as well as excessive noise and other psychosocial factors. Similarly lack of exposure to sunlight in UG environments may lead to a plethora of conditions ranging from minor illnesses and reduced sleep quality to more chronic conditions such as CVD, respiratory diseases, mental disorders or cancers (Parent, El-Zein et al. 2012, Vyas, Garg et al. 2012, Gan, Yang et al. 2014, Anothaisintawee, Reutrakul et al. 2016). It is widely believed that these negative health outcomes are mediated through low MLT levels (Stevens and Rea 2001, Haim

and Portnov 2013, Hurley, Goldberg et al. 2014, Stevens, Brainard et al. 2014, Haim and Zubida 2015, Kim, Lee et al. 2015), (Kecklund and Axelsson 2016). Potential explanation involves suppression of melatonin secretion via artificial LAN or decreased exposure to natural sunlight during the day leading to chronodisruption and insufficient sleep quantity and quality.

While there is a large and growing body of evidence on the health effects of circadian disruptions, shift working and LAN (Driesen, Jansen et al. 2010, Wulff, Gatti et al. 2010, Evans and Davidson 2013), very few studies investigated these mechanisms in UG environments. Similarly, there is very limited research evidence comparing AG and UG environments in terms of their health effects. Nonetheless we believe there might be an overlap between the effects (or risk factors) of UG environments and those of e.g., windowless AG environments. For instance, either exposure to excessive noise can happen at AG construction site or in UG space; poor air quality can take place either at windowless office or in UG location. We found only five studies comparing the health effects of UG environments with AG. These studies were however heterogeneous in terms of study designs employed, populations evaluated and outcomes measured; and reported inconclusive results. The biggest and most generalizable study was reported significantly higher levels of insomnia, sleep problems, somnolence, and feeling sleep deprived in UG workers compared with AG (Leger, Bayon et al. 2011).

We argue that artificial light at UG environments should mimic (as much as possible) the natural sunlight thereby mitigating the negative health effects discussed herein. In addition, there is a growing evidence that modern artificial lighting, especially LEDs, with wavelengths differing from those in sunlight produces or exacerbates circadian disruptions. Workers in UG environments are more likely to be exposed solely to artificial lighting and so are potentially at greater risk. New lighting technologies, which replicate sunlight spectrum, are becoming available, but they are still expensive and should be subject to experimental studies and health economic analyses. Other design strategies to alleviate negative psychological and physiological

effects of UG space include enhancing the sense of space, view and orientation through the use of glass partitions, higher ceilings, multi-level spaces, central atrium and optical devices; various beamed daylighting systems or full spectrum artificial light; interior design elements such as brighter colours, plants, fountains or artworks (Carmody and Sterling 1987, Roberts, Christopoulos et al. 2016).

Strengths and limitations

This review has important strengths including comprehensive searches of published and unpublished literature over the past 37 years. However, several limitations should be kept in mind when interpreting results of this review. First and foremost, we did not apply any specific exclusion criteria for deciding which studies to exclude from the review. Secondly, no formal validity/risk of bias assessments were planned and performed. Thirdly, from the conceptual perspective, many of the health effects and environmental exposures (in both AG and UG spaces) overlap with one another and it was challenging to classify those. For example, shift working, artificial LAN and light wavelengths are also circadian disruptions. Similarly, because of limited number of studies evaluating the health effects of UG spaces, the health effects discussed are hypothetical and so are classifications of UG and AG working environments that often overlap.

5 Conclusions

We need to expand our knowledge on the actual health effects of working in UG environments. Although five observational studies have reported predominantly, detrimental health effects of UG environments compared with AG spaces, these were mainly short-term, mostly based on self-reported data, and the findings were not conclusive. Larger experimental studies examining the medium- and long-term health effects of working in diverse UG locations; with a range of

environmental measures, periods of exposure and populations are needed. These studies will further inform employers and employees, designers or policy makers.

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Figure 1. Overview of the possible health effects associated with working in underground spaces

Table 1. Potential (or actual) health effects of working in underground spaces with mechanisms of action involved and suggested explanations

Study (reference)	Potential (or actual) health effects	Exposure	Mechanism of action/ Explanation
(Küller and Wetterberg 1996, Ehrine J.P. Manzana 2001, Young 2007, Driesen, Jansen et al. 2010, Wulff, Gatti et al. 2010, Leger, Bayon et al. 2011, Parent, El-Zein et al. 2012, Vyas, Garg et al. 2012, Evans and Davidson 2013, Wang, Yeung et al. 2013, Gan, Yang et al. 2014, Anothaisintawee, Reutrakul et al. 2016, Proper, van de Langenberg et al. 2016)	Metabolic diseases (obesity, type II diabetes); various cancers; psychiatric and neurodegenerative disorders; coronary heart disease; stroke; mood swings; poor sleep quality	Shift working (artificial light at night) and circadian disruption (chronodisruption)	Suppression of melatonin secretion; decreased exposure to sunlight (underexposure)
(Shuster, Chadwick et al. 1982, S Sarikaya 2006, Holick 2007, Llewellyn, Lang et al. 2011, Annweiler, Rolland et al. 2012, Smith, Abrams et al. 2014, Baggerly, Cuomo et al. 2015, Banerjee, Khemka et al. 2015, Wamberg, Pedersen et al. 2015, Ukabiala, Alkureishi et al. 2016)	Decreased bone mineral density, dementia, Alzheimer's disease, inflammatory bowel disease; type II diabetes	Vitamin D deficiency	Reduced sunshine exposure, lifestyle factors, inadequate dietary patterns
(WHO 1988, Xueyuan and Yu 1988, Wada and Sakugawa 1990, Küller and Wetterberg 1996, Ooi, Goh et al. 1998, Field, Steck et al. 2000, Passchier-Vermeer and Passchier 2000, Wang, Lubin et al. 2002, Stansfeld and Matheson 2003, Kulich, Rericha et al. 2007, Fisk, Eliseeva et al. 2010, Bahn 2013, Hansell, Blangiardo et al. 2013, Jenny Selander 2013, Sahlberg, Gunnbjörnsdottir et al. 2013, Jung, Liang et al. 2014, Liu, Wang et al. 2014, Olesen 2014, Olesen 2014, de Souza, Périssé et al. 2015, Bansah, Yalley et al. 2016, Legault, Clement et al. 2017, Yu, Chen et al. 2017)	Respiratory or cardiovascular diseases; cancers; headaches, fatigue, and cognitive problems; decreased working efficiency; hearing impairment, sleep disturbance; poor mental health	Sick building syndrome	Poor ventilation systems and influx of outdoor pollutants such as SO ₂ , NO _x , CO, CO ₂ , ozone, radon; volatile organic compounds, pesticides, and particulate matter; excessive noise; psychosocial factors

Table 1 footnote: CO- carbon monoxide, CO₂- carbon dioxide; NO_x- nitrogen oxides; SO₂- sulphur dioxide