Update of the Scientific Evidence for Specifying Lower Limit Relative Humidity Levels for Comfort, Health and IEQ in Occupied Spaces (RP-1630)

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Abstract

Nearly 600 papers were located in citation and keyword searches regarding the effects of humidity on comfort, health, and indoor environmental quality (IEQ). Of these, around 70 papers reported the effects of low humidity (RH≤40%) and were analyzed in detail. Information in some categories was well chronicled, while other categories had significant knowledge gaps. Low humidity decreased house dust mite allergens. Due to different envelopes, generalizations could not be made for all bacteria and viruses. However, lower humidity increased virus survival for influenza. For comfort, low humidity had little effect on thermal comfort, but skin dryness, eye irritation, and static electricity increased as humidity decreased. For IEQ, low humidity had non-uniform effects on volatile organic compound (VOC) emissions and perceived indoor air quality. Across many low humidity studies, ventilation rates and exposure times were noted as confounding variables. A majority of studies that used human subjects utilized exposure times of three hours or less with adult subjects; few studies used children, adolescents, or elderly subjects.

1. Introduction

Humidity levels in indoor environments affect occupant health, comfort, and indoor environmental quality (IEQ). High humidity can reduce human comfort and impact disease transmission (Sterling et al., 1985; Berguland, 1998). In response to tightly sealed buildings to reduce building energy consumption, upper limits on relative humidity (RH) have been prescribed for human comfort and to mitigate growth of mold and fungi in buildings (ASHRAE, 2012) . However, low humidity can also cause discomfort for building occupants (e.g., dry skin, dry eyes, dry nose). Low humidity also has implications for disease transfer, allergies, and respiratory functions, although firm, scientifically-grounded conclusions regarding the effects of low humidity are challenging to find. The literature review by Sterling et al. (1985) considered aspects of low humidity on building occupants, but there is a clear need to compile and analyze

data in the recent literature to determine the effects of low humidity (≤ 40% RH) on building occupants.

1.1 Research objectives

The purpose of this study is to conduct a broad survey of post-1985 literature regarding the effects of low humidity on comfort, health, and IEQ. The research objectives of the literature review are to identify existing knowledge and knowledge gaps, as well as confounding variables. Nearly 600 papers were collected as a result of keyword and citation searches. General criteria for further paper analysis included the following:

- At least one data point where RH ≤ 40%
- New data
- Report temperature
- Controlled study
- Focus on healthy, human subjects
- Residences and workplaces

Many studies that utilized surveys and environmental sampling (e.g., IAQ, dust mites, VOCs) were included for further analysis if the mean indoor RH was below 40%; this condition frequently occurred indoors during heating season in northern regions. Since the Sterling et al. (1985) study addressed previous literature, the focus of this analysis was on papers with publication dates after 1985. A few pre-1985 papers were included because they presented unique data and were frequently referenced by more recent papers. The paper collection phase ended in mid-2015. Review papers related to the effects of low humidity were read, and additional papers were found from their citations; however, review papers were not analyzed in depth because they did not contain new data.

1.2 Literature review approach

The literature review was conducted iteratively, and a brief description follows. First, papers were identified using keyword and citation searches and classified into health, comfort, and IEQ categories. An extensive keyword search was conducted to locate low humidity studies searching Engineering Index (Compendex), Web of Science, and Google Scholar. The searches used “low humidity” and additional keywords given in Table 1. In addition, it was determined

that the phrase "dry air" returned useful results. The compiled literature was reviewed by the multi-disciplinary author team and additional searches were conducted based on the feedback. A draft report was distributed to a broad review panel for feedback from external reviewers; their feedback was incorporated into this paper.

After the initial keyword search was conducted, key papers from each category were identified (Table 2). Key papers typically 1) contained data, 2) utilized a control in a low humidity environment, 3) were the best paper in a given category at the time, or 4) were a review paper. Key papers were not limited to post-1985 publication dates. A citation search was conducted for key papers in both Scopus and Google Scholar including reverse and forward citations. Typically, five to ten papers were added from the citation search for each key paper. Of the nearly 600 papers located by the keyword and citation searches, around 70 met the criteria for further analysis. The following sections discuss and analyze literature regarding the effects of low humidity on health, comfort, and IEQ.

2. Health

Health effects included asthma, respiratory infections, and allergies, as well as pathogens and disease transmission.

2.1 Asthma and respiratory infections

The asthma and respiratory literature utilized laboratory testing, environmental sampling, and surveys, but addressed limited humidity levels (Figure 1). Two review papers examined the effects of dehumidification on asthma patients (Singh et al., 2002; Singh and Jaiswal, 2013), yet only located one or two papers, and the effects of dehumidification were inconclusive. A laboratory study examined eight male university students in an environmental chamber (Andersen et al., 1974). Subjects spent 27 hours at 23 ^{o}C (73.4 ^{o}F), 50% RH, 78 hours at 23 ^{o}C (73.4 ^{o}F), 9% RH, followed by 20 hours at 23 ^{o}C (73.4 ^{o}F), 50% RH. The researchers measured nasal mucociliary flow using detection of small particles (technetium Tc 99m-tagged resin particles), and did not find a statistically significant difference in nasal mucus flow rates between the humidity levels with this method. Laboratory research (Bundgaard et al., 1982; Kaminsky et al., 1995) focused on determining the mechanism of exercise-induced asthma. Bundgaard et al. (1982) studied 10 subjects with exercise induced asthma at two temperatures [15 ^{o}C (59 ^{o}F) and 30 ^{o}C (86 ^{o}F)] and two humidity levels (30% and 70% RH), noting the lowest reduction in peak expiratory flow (PEF) at T=30 ^{o}C (86 ^{o}F) and 70% RH. Kaminsky et al. (1995) tested warm [T=

37 °C (98.6 °F)], saturated air, followed by five minutes of 22 °C (71.6 °F) dry air, and a recovery period of 45 minutes of warm saturated air. In the study, the dry air test also included a lower air temperature, and the results are confounded by the effects of temperature. Peripheral resistance, a measure of flow restriction, was significantly higher in asthmatics (*N*=8) compared to healthy subjects (*N*=8). Both papers indicated that asthmatics are more sensitive to cool, dry air, but few humidity conditions were tested.

Several studies (Charpin et al., 1988; Ezeamuzie et al., 2000) examined the link between asthmatics and allergens in environments with dry (RH< 40%) conditions. Ezeamuzie et al. (2000) studied human subjects in Kuwait, where summer conditions are warm [mean temperature of 42 °C (107.6 °F)] and dry (15–30% RH). They measured immune response, IgE, to 14 allergens for asthmatics and matched controls, determining that 87% of asthmatics were sensitive to one or more allergens, compared to 24% of the control group. Sensitization to house dust mites was also higher than expected for asthmatics. Charpin et al. (1988) surveyed thousands of people in Marseille, France and Briançon, France. Briançon is located in the Alps at an elevation of 1350 m with winter humidity averaging 35% RH. Subjects randomly received a skin prick for *D. pteronyssinus* dust mites. Of those surveyed, 4.1% and 2.4% of subjects had asthma and 27.5% and 10.2% tested positive for dust mite allergies in Marseille and Briançon, respectively. The authors suggested that altitude or lower humidity in Briançon may reduce dust mite allergens and asthma.

Three studies (Infante-Rivard, 1993; Smedje et al., 1997a; Kovesi et al., 2007) focused on understanding the effects of environmental conditions on young asthmatics and children with a history of lower respiratory tract infections (LRTIs). Kovesi et al. (2007) studied Inuit children (< 5 years old). Measurements were taken in homes with (*N*=49) and without (*N*=46) children during heating season in Nunavut, Canada. Outdoor mean winter temperatures were -20 °C (-4 °F) and indoor conditions were 25 °C (77 °F), 30% RH. Researchers observed that average ventilation rates were low [5.6 L/s per person (11.9 cfm)] and RH was negatively associated with ventilation rates per person. In addition, high indoor CO_2 levels increased risk for LRTI, leading the authors to conclude that adequate ventilation is important. Infante-Rivard (1993) conducted a phone survey with newly diagnosed asthmatic children (3–4 years old) and matched controls in Montreal, Canada. Researchers noted an increased prevalence of asthma with a humidifier in a child's bedroom, but decreased asthma risk with central humidification. The humidifier had

mixed effects on subjects and therefore no strong conclusions could be drawn from this study. Smedje et al. (1997) surveyed Swedish teenagers (13–14 years old) and took measurements in public school classrooms with an average temperature of 24 ^{o}C (75 ^{o}F) and 37% RH. Of the 672 pupils surveyed, 6.4% were asthmatics. The highest correlation was found between the length of open shelving to room volume (shelf factor), cat dander allergens, and viable bacteria. Low temperatures, higher relative humidity, and increased concentrations of formaldehyde and VOCs, which are indicative of lower ventilation rates, correlated with a higher incidence of asthma. These studies indicated that environmental conditions can significantly impact asthmatic children and youth; however effects of low humidity were not well documented and require further investigation.

2.2 House dust mites (HDM)

Dust mites are dependent on moisture in the air for survival, and are therefore susceptible to low humidities (Crowther et al., 2000; Milián and Díaz, 2004). House dust mite literature consisted of laboratory tests (Arlian, 1992; Arlian et al., 1998), and environmental sampling of dust mite allergens (Munir et al., 1995; Sundell et al., 1995; Arlian et al., 2001; Howieson et al., 2003), with test conditions shown in Figure 2. Arlian (1992) studied *D. farinae, D. pteronyssinus,* and *E maynei* house dust mites at room temperature [T=20 ^{o}C (68 ^{o}F)] and multiple humidities (22.5%, 65%, 75%, 80%, 85%, and 95% RH). As RH increased, water obtained from the air by the mites went from 0.01 μg at 22.5% RH to 1.55 μg at 95% RH. The increase in water consumption and increase in feeding rates at higher humidities corresponded to more fecal pellets that contained house dust mite allergens. A humidity level of 22.5% RH reduced mite survival and allergens. Subsequently, Arlian et al. (1998) studied *D. farinae* mites at room temperature [T=20 ^{o}C (68 ^{o}F)]. Tests at constant 0% RH and 75% RH served as controls, and tests were conducted for 2, 4, and 8 hours at 75% RH, with the rest of the 24-hour day at 0% RH. With a brief (2 or 4 hour) exposure to 75% RH, dust mites were unable to complete the entire life cycle, but they laid eggs and many adult females survived. With 8 hours at 75% RH, the mites had sufficient moisture to complete their lifecycle. Based on this study, brief exposures to high humidity resulting from cooking or showering, for example, can promote dust mite survival.

Two studies (Munir et al., 1995; Sundell et al., 1995) sampled dust mites from homes in Sweden. Munir et al. (1995) surveyed 130 homes with asthmatic children in distinct climates in northern, central, and southern Sweden. They sampled dust mites and allergens from 20 homes

in each region. Der p I and Der f I allergens were most prevalent in the southern region where humidity was higher. They determined that a specific humidity of 7 g/kg, RH > 45%, and ventilation rates less than 0.5 air changes per hour (ACH) contributed to higher dust mite allergen concentrations. Sundell et al. (1995) measured house dust mite allergen levels for 18 homes with low HDM allergen levels (<1000 ng/g) and 11 houses with high dust mite levels (> 2000 ng/g). Average absolute humidity was 1.9 g/m^3 and 2.6 g/m^3 in low and high infestation group homes, respectively. Low infestation homes also had higher bedroom ventilation rates of 0.9 ACH, compared to 0.2 ACH in higher infestation homes, although all homes had comparable average ventilation rates. Although the authors noted a statistical difference in absolute humidity between low and high HDM infestation homes, absolute humidity was extremely low in both groups.

Arlian et al. (2001) studied HDM allergens in 71 Ohio homes over 17 months, including two summers. Homes employed dehumidifier and air conditioning, only air conditioning, or natural ventilation. Allergen density was significantly lower in homes where RH was less than 50%, including during moist summers in which mite populations surged in the higher humidity group. Similarly, a study by Howieson et al. (2003) in the United Kingdom recommended indoor humidities less than 60% to reduce dust mite allergens and improve asthma. This research demonstrated that controlling home humidity levels may effectively reduce HDM allergens.

2.3 Introduction to microbiology

For infectious pathogens, three primary approaches were used to quantify viability as a function of environmental variables: laboratory tests of aerosolized pathogen viability, transmission studies with animal models, and large epidemiology studies relating disease metrics (e.g. influenza mortality cases) to outdoor weather conditions with an imposed time lag.

Several routes of transmission and infection have long been hypothesized (i.e., direct contact, fomite, droplet, droplet nuclei); very few organisms are known to be transmitted solely by one route, and RH can uniquely affect each of these transmission modes. Because one goal of this study was to define updated criteria for human exposure in occupied buildings in terms of humidity, literature investigating a broad set of pathogens (including influenza and pneumonia) was surveyed. Nonetheless, it is outside the scope of this work to produce criteria for all organisms that contribute to nosocomial infections.

Many confounding variables were identified that impact the effects of low humidity on pathogen viability and transmission. This literature survey as designed did not account for all important factors for quantifying health effects at low levels of humidity. These factors include variation in air exchange rate, length of organism exposure, variation in the biological structure and routes of entry, variation of pathogen survival on different fomites, and variances in human host response. This study briefly investigated organism survival on fomites, but organism survival and transmission potential depend on fomite material and structure, as well as humidity, temperature, and length of exposure. Several studies assumed that detection correlates with infection, while other studies were based on transmission rates. Because many studies were designed with independent hypotheses, it is at times not possible to generalize findings based on the extant literature.

2.4 Bacteria

Although several low humidity studies were obtained during the literature search, many studies focused on pneumonia in humid environments (Onozuka et al., 2009; Negrisoli and Nascimento, 2013; Ramos, 2013). In laboratory tests, four studies considered aerosol viability (Dunklin and Puck, 1948; Wright et al., 1968; Theunissen et al., 1993; Ko et al., 2000) and one study examined the spread of pathogens on fomites (Lopez et al., 2013), with conditions shown in Figure 3. The aerosol studies primarily examined aerosol size and bacteria viability, with lowest viability around 50% and a bathtub-shaped curve. However, direct comparison was challenging due to different starting concentrations and lethality levels amongst organism types. In the last decade, interest and research has increased regarding the effects of ultraviolet light to inactivate bioaerosols at different relative humidities (Ko et al., 2000; Peccia et al., 2001; Fletcher, 2004).

Two epidemiology studies were conducted (Mäkinen et al., 2009; Davis et al., 2012). The epidemiology study by Davis et al. (2012) related pneumonia and influenza deaths to outdoor weather conditions in the New York City metro area from 1975 to 2002. Although they found an interesting correlation with low dewpoint temperatures, no humidity limits for interior spaces could be drawn since outdoor humidity differs from indoor conditions. Makinen et al. (2009) correlated LRTIs and URTIs with outdoor weather conditions for Finnish military conscripts who trained outdoors. The study was unique because conscripts trained outdoors and reported only to the military base medical center. In the three days preceding the onset of a RTI, mean

outdoor absolute humidity was around 4 g/m^3, and a 1 g/m^3 decrease in absolute humidity increased estimated URTI risk by 10%.

2.5 Viruses

The virus literature featured a combination of laboratory testing (Akers et al., 1966; Lowen et al., 2007; McDevitt et al., 2010; Yang et al., 2012; Noti et al., 2013; de la Noue et al., 2014), epidemiology (Shaman and Kohn, 2009; Shaman et al., 2010; Barreca and Shimshack, 2012; van Noort et al., 2012; Jaakkola et al., 2014), modeling (Shaman and Kohn, 2009; Yang and Marr, 2011), and review papers (Morawska, 2006; Brankston et al., 2007; Weber and Stilianakis, 2008; Tang, 2009; Memarzadeh, 2012; Yang and Marr, 2012); test conditions are shown in Figure 4. The review paper by Weber and Stilianakis (2008) identified three methods of transmission: droplet (sneezing or coughing), airborne, and contact; the review paper by Brankston et al. (2007) also discussed influenza survival and transmission.

In laboratory tests, mid-range humidity of approximately 50% RH was shown to reduce virus viability for Columbia SK viruses (Akers et al., 1966), murine norovirus (MNV) (de la Noue et al., 2014), and influenza (Hemmes et al., 1962; Yang et al., 2012), as is consistent with the conclusions of Weber and Stilianakis, 2008. Several studies considered influenza transmission (Lowen et al., 2007; Noti et al., 2013; Lowen and Steel, 2014). Lowen et al. (2007) demonstrated reduced influenza transmission at 50% RH compared to 20% and 35% RH in a guinea pig model. Transmission increased with decreasing temperature. In a subsequent paper, Lowen and Steel, 2014 analyzed the data as a function of absolute humidity instead of RH; they did not observe a trend with absolute humidity. Noti et al. (2013) simulated influenza transmission via coughing using manikins, and observing five times more infectious virus in the low humidity range (7%–23% RH) than above 43% RH. The evidence suggested that influenza viability and transmission is higher at lower humidities, with minimal transmission and survival occurring at midrange relative humidities (around 50% RH). Modeling by Yang and Marr (2011) suggested that ventilation rates are important; at high values, ventilation can be a dominant removal mechanism of airborne viruses, especially those found in smaller droplets that are less effectively removed by gravitational settling. The review paper by Morawska (2006) reinforces the idea that droplet size and virus envelope composition are important for disease transmission.

In general, epidemiology studies correlated influenza mortalities and occurrences with outdoor weather station data. Barreca and Shimshack (2012) correlated outdoor weather data to influenza mortalities in 359 counties in the United States, observing that lower specific humidity was a risk factor for influenza mortality. Jaakkola et al. (2014) studied Finnish military recruits. A 0.5 g/m^3 decrease in absolute humidity increased influenza risk by 58%, but extremely low temperatures [< -10 ^{o}C (< 14 ^{o}F)] and absolute humidity (3 g/m^3) reduced influenza risk, indicating nonlinear effects of humidity on influenza transmission. van Noort et al. (2012) noted an effect of outdoor absolute humidity on influenza-like illness in two independent data sets (European Influenza Surveillance Network and Influenzanet). These epidemiology studies highlight an influence of absolute humidity on influenza using outdoor weather data. Shaman et al. (2011), Shaman et al. (2011), and Shaman and Kohn (2009) conducted studies with large influenza data sets, and using outdoor weather conditions, they found that influenza was dependent on absolute humidity. Shaman and Kohn (2009) suggested that influenza virus survival is better explained by absolute humidity because it is influenced by evaporation and droplet size. From these studies, the conclusion was made that a relationship exists between outdoor absolute humidity and influenza. Indoor absolute humidity is determined by the ventilation rate, outdoor absolute humidity, and humidity source generation. Due to the confounding variables, it is inappropriate to draw conclusions from outdoor humidity conditions and apply them to indoor conditions, unless indoor humidity was measured.

2.6 Fungi

Three papers (Pasanen et al., 1991; Ezeonu et al., 1994; Górny et al., 2002) reported laboratory testing related to mold and fungi at low humidity (<40% RH), and one review paper was identified (Arens and Baughman, 1996). The vast majority of papers located through the keyword searches in this category tested the upper humidity ranges (>80% RH) in humid climates (Pei-Chih et al., 2000; Wu et al., 2005; Elbert et al., 2007; Sousa et al., 2008). In low humidity literature, Ezeonu et al. (1994) and Gorny et al. (2002) tested growth on building materials such as fiberglass and ceiling tiles, respectively, while Pasanen et al. (1991) considered fungal spore emission and aerosolization. Gorny et al. (2002) determined the effects of ventilation, and noted that small (< 1.6 μm) fungal particles were easily aerosolized at room temperature and a humidity range of 32–40% RH. Ezeonu et al. (1994) studied fiberglass material samples over a wide humidity range (35–97% RH) and noted no fungal colonization at 35%

RH. Pasanen et al. (1991) also determined that low RH can increase fungal spore release for some strains and that air velocity has a strong impact on fungal spore aerosolization. The review by Arens and Baughman (1996) suggested that fungi growth and propagation is dependent on surface conditions rather than air conditions.

3. Comfort

3.1 Eye irritation

The focus of the literature review was to determine the effects of low humidity on healthy eyes (Laviana et al., 1988; McCulley et al., 2006; Sunwoo et al., 2006a; Wyon et al., 2006; Arciniega et al., 2011; Abusharha and Pearce, 2013), although several papers were located that addressed the effects of humidity on subjects with dry eyes (Mathers and Daley, 1996; Borchman et al., 2009; Arciniega et al., 2011; Galor et al., 2011; Tomlinson et al., 2013). In addition, the effects of contact lenses were not the main focus of this study, but have been studied by several researchers (Laviana et al., 1988; Tsutsumi and Tanabe, 2002). Most studies considered few humidity conditions (Figure 5). Two studies used eye goggles to test eye responses to increasing humidity (McCulley et al., 2006; Arciniega et al., 2011); it is not clear if the goggles limited secretion of aqueous tear film components or if fluorescein or other eye drops were administered, thereby affecting affect tear production. When comparing evaporation rates with relative humidity between 25–35% to evaporation rates with humidity between 35–45% RH, Arciniega et al. (2011) and McCulley et al. (2006) observed small increases in tear film evaporation at the lower humidity level.

In controlled testing in an environmental chamber, Abushara and Pearce (2013) noted substantially higher tear film evaporation rates and eye discomfort at 5% RH compared to 40% RH in a small cohort (N=12). At the lower humidity levels, evaporation rates in healthy eyes were commensurate with expected evaporation rates in eyes with dry eye syndrome. Subjects in the study by Laviana et al. (1988) indicated no significant changes in eye comfort for healthy eyes without contacts between 10% and 30% RH. In the study by Sunwoo et al. (2006a) blink frequency was higher at 30% RH and 10% RH than it was at 50% RH, but they did not address whether visual acuity was affected by environmental conditions. Wyon et al. (2006) conducted a thorough study using a mucus ferning test which indicated eyes were drier at 5% and 15% RH compared to 25% and 35% RH at room temperature, suggesting that RH greater than 15% is preferable. Although the subjects' eyes were drier at 5% RH, the subjects did not perceive a

difference in dryness compared to 35% RH, and small but statistically significant decreases in performance of office tasks (e.g., typing speed, proofreading, and addition) were found at lower humidity levels.

3.2 Skin dryness

A majority of studies investigated skin dryness in offices and workplaces (Reinikainen et al., 1991; Nordström et al., 1994; Reinikainen and Jaakkola, 2003; Chou et al., 2005; Chou et al., 2007), with a few laboratory studies conducted in environmental chambers (Sunwoo et al., 2006a; Wyon et al., 2006). This literature review focused on healthy subjects without underlying conditions such as eczema (Eberlein-König et al., 1996). Environmental conditions are presented in Figure 6. Several studies (Chou et al., 2005; Chou et al., 2007) dealt with workers in an ultra-low humidity environment [T=23.6 ^{o}C (74.5 ^{o}F), 1.5%–2.5% RH], with age-matched controls who worked in a neighboring office [T=25 ^{o}C (77 ^{o}F), 60% RH]. The ultra-low humidity environment was a battery factory, and chemicals and processing may have confounded study results. However, the studies were controlled studies that investigated a unique humidity condition over several years. Over time, skin adapted to the drier conditions, although itching was more common, and there were possible signs of dehydration.

Nordstrom et al. (1994) and Reinikainen et al. (1991 and 1993) studied Swedish geriatric hospital employees and Finnish office workers, respectively. In the study by Nordstrom et al. (1994) workers were divided into a humidified group (40–45% RH) and control (25–35%). After humidification, dry air complaints dropped significantly, and a general reduction of perceived dryness and some dryness symptoms occurred. However, humidification did not have a strong impact on perceived IAQ. In the study by Reinikainen et al. (1991), humidifiers were installed in two office wings; one wing was randomly selected to be humidified each week. Humidification reduced nasal congestion, but reductions in skin, nasal, and pharyngeal dryness were not statistically significant. However, humidification increased sensation of odor and stuffiness. In these studies, humidity differences between humidified and control group were modest (~10% RH).

The laboratory study by Sunwoo et al. (2006a) noted significant effects of humidity and time on transepidermal water loss (TEWL). At 10% and 30% RH, TEWL increased after 30 minutes and then stabilized. Tests were conducted for 2 hours, so skin adaptation over longer time periods could not be extrapolated. In the study by Wyon et al. (2006), skin dryness and

throat irritation were exacerbated at 15% RH with polluted air. These laboratory studies indicated a change in TEWL and skin dryness at lower RH.

3.3 Thermal comfort

The keyword and literature search yielded many papers that examined thermal comfort above 40% or 60% RH (Ahmed, 2003; Wong and Khoo, 2003; Hwang et al., 2006; Han et al., 2007; Becker and Paciuk, 2009; Shinohara et al., 2014). Six papers were identified that studied thermal comfort in chambers with set environmental conditions at low (RH <40%) humidities (Nevins et al., 1966; de Dear et al., 1989; Fang et al., 1998; Sunwoo et al., 2006a; Sunwoo et al., 2006b; Tsutsumi et al., 2007), and noted the effects of clothing on thermal comfort. The thermal comfort category included a far wider range of test conditions than any other category, demonstrated in Figure 7.

In the pioneering study by Nevins et al. (1966), subjects were college students (*N*=720) wearing standardized clothing. Subjects were sedentary during the 3-hour test, and conditions were tested at nine temperatures [18.9–27.7 ^{o}C (66–82 ^{o}F)] and eight humidity levels (15-85% RH). The authors demonstrated that humidity has a minimal effect on thermal comfort at low humidities. However, this conclusion is limited to the conditions of the study, namely the third hour of a three hour, steady-state exposure with truly sedentary activity. Work by de Dear et al. (1989) was a landmark study that examined the effects of humidity transients as subjects moved between 20% RH and 80% RH chambers at 23.3 ^{o}C (74 ^{o}F). Subjects felt cooler when transitioning from 80% RH to 20% RH, and effects were more pronounced when subjects were wearing absorbent clothing (e.g., wool). The effect of the humidity transient on thermal comfort lasted up to 90 minutes. These study results are important because they document the large effect of humidity when people move from a low humidity environment to high humidity environment (and vice versa), although these results are challenging to directly apply because of the complexity of adding time as a variable. Similarly, in the study by Tsusumi et al. (2007), subjects moved from chamber 1 at 30 ^{o}C (86 ^{o}F), 70% to chamber 2. In chamber 2, the Standard Effective Temperatures (SET*) was kept constant at 25.2 ^{o}C (77.4 ^{o}F), but humidity was varied (30%, 40%, 50%, 70% RH). After transitioning to the second chamber, subjects felt cooler. Subjects performed tasks to assess productivity, and there was no statistically significant difference in productivity between 30% and 70% RH conditions. The study by Fang et al. (1998) examined odor perception and thermal comfort in a range of temperatures [18–28 ^{o}C (64.4–82.4 ^{o}F)] and

humidities (30%, 50%, and 70% RH). They determined that air acceptability decreased with increasing temperature and RH, perhaps suggesting an effect of absolute humidity. However, thermal comfort was not affected by conditions as subjects adjusted clothing.

Sunwoo et al. (2006a) conducted comfort studies on 16 college-aged men, and an additional study by Sunwoo et al. (2006b) studied eight college-aged men and eight elderly men (average age 72). For both studies, subjects were seated in rooms at 25 ^{o}C (77 ^{o}F), with 10%, 30%, or 50% RH. In the Sunwoo et al. (2006a) study, they observed effects of low humidity on saccharin clearance time (SCT), blink frequency, and hydration. However, no changes in thermal comfort were observed. In Sunwoo et al. (2006b) research, many trends were identical between the younger and elderly group; however, the young group felt cooler (whole body thermal comfort) than the elderly group.

3.4 Static electricity

A few papers studied the effects of low humidity on static electricity (Norbäck et al., 1990; Nordström et al., 1994; Paasi et al., 2001). Paasi et al. (2001) studied resistivity and electrostatic discharge time for many materials such as standard corrugated cardboard, electrostatic discharge (ESD) cardboard, ESD plastic, ESD textiles, safety fabric, 100% cotton, and 100% polyester at room temperature for 10 relative humidities ranging from 5–70%. For most materials, electrostatic discharge was a concern below 20–30% RH. In a different approach, Norback et al. (1990) and Nordstrom et al. (1994) conducted surveys of building workers in which static electricity was a parameter of interest. Norback et al. (1990) found that static electricity correlated with sick building syndrome symptoms during the heating season in Sweden. Nordstrom et al. (1994) observed that static electricity complaints in the humidified group [40–45% RH, T~22 ^{o}C (71.6 ^{o}F)] were half that of the control group [25–35% RH, T~22 ^{o}C (71.6 ^{o}F)].

4. Indoor environmental quality

Eleven papers were identified which studied IEQ, perception of IAQ, and VOCs at low humidities using several research approaches are presented in Figure 8. Four used human subjects (Kay et al., 1990; Fang et al., 1998; Cain et al., 2002; Fang et al., 2004), two directly studied emissions from building materials, and five conducted surveys in buildings with low RH (Norbäck et al., 1990; Reinikainen et al., 1992; Sundell and Lindvall, 1993; Smedje et al., 1997b; Fiedler et al., 2005). Some studies complemented survey results with building testing of VOCs

and other IEQ conditions, and many of these studies were motivated to determine the causes of sick building syndrome.

Results on the effects of RH on VOC emissions from building materials were inconclusive and dependent on the type of material and type of VOC (Wolkoff, 1998; Fang et al., 1999; Cain et al., 2002). Fang et al. (1999) studied PVC flooring, acrylic floor varnish, polyamide carpet, acrylic wall paint, and acrylic sealant, and found limited effects of humidity (30%, 50%, and 75% RH) on VOC emissions from these materials, while lower RH increased VOC emissions from acrylic floor varnish and wall paint. Similarly, Cain et al. (2002) tested building materials (i.e., carpet, particle board, plywood, plaster wallboard, vinyl tile). TVOC concentrations in the chamber did not change much when RH increased from 35% to 70% at room temperature [T=22.5 ^{o}C (72.5 ^{o}F)]. Wolkoff (1998) considered three temperatures at 0% and 50% RH. Temperature and RH significantly influenced emissions but depended highly on type of material and VOC. Little effect of humidity (0% versus 50% RH) was observed on emissions from tested building materials, except plasticizers.

In general, studies have found that increasing temperature and RH decreases the perceived quality or acceptability of the air, although results are not conclusive concerning odors and sensation of dryness (Kay et al., 1990; Reinikainen et al., 1992; Sundell and Lindvall, 1993; Fang et al., 1998; Nagda and Hodgson, 2001; Cain et al., 2002; Fang et al., 2004). Cain et al. (2002) noted perceived odor intensity increased with an increase in humidity from 35% to 70% RH. Fang et al. (1998, 2004) determined that that perceived air quality decreased with increasing air temperature and humidity but perceived odor intensity was not affected by environmental conditions. Reinikainen et al. (1992) employed humidification (45–55% RH) in offices, reducing complaints of dryness compared to periods without humidification (10–25% RH). In contrast, Sundell and Lindvall (1993) and Kay et al. (1990) did not find a strong correlation between sensation of dryness and RH. Nagda and Hodgson (2001) wrote a review of low humidity environments, specifically low humidity aircraft cabins and buildings. They noted that subjects were often unable to detect low humidity, and that low humidity was not extremely noticeable on short (<3 hour) flights. In buildings, they suggested a modest 10% RH increase could mitigate some dryness symptoms.

Few studies (Grøntoft and Raychaudhuri, 2004; Fiedler et al., 2005) have examined the relationship between low humidity and ozone. In the study by Fiedler et al. (2005) subjects

experienced a one-time, three hour exposure to a mixture of VOCs (with and without O_3) at a temperature of 25.5 ^oC (78 ^oF) and 36.5% RH. Subjects did not have any significant subjective or objective health effects as a result of the pollutants; stress was more detrimental than the pollutants. Grontoft and Raychaudhuri (2004) studied ozone deposition velocities at five humidity levels (0–90% RH). Ozone deposition velocities increased as humidity increased from 0% to 30% to 50% RH for most materials (e.g., glass, stone, coarse concrete, woodwork, wool carpet, wallpaper). However, ozone deposition velocity decreased as RH increased from 0% to 50% for fine concrete. Reviews of indoor chemistry and ozone (Weschler, 2006; Uhde and Salthammer, 2007) contained limited discussion of the effects of humidity.

5. Discussion

5.1 Knowledge gaps

Primary research objectives were to identify existing knowledge, knowledge gaps, and confounding variables pertaining to health, comfort, and IEQ. A brief discussion follows. General conclusions can be drawn for house dust mites, influenza, and thermal comfort at low activity levels. Data in the HDM literature support the conclusion that higher humidity levels encourage dust mite growth and subsequent HDM allergen production (Arlian, 1992; Arlian et al., 1998; Arlian et al., 2001), because dust mites obtain moisture from the air for survival. Dust mites can survive and reproduce with brief periods of high humidity in otherwise dry environments (Arlian et al., 1998). HDM allergens were significantly reduced when humidity was below approximately 50% or 60% RH (Arlian et al., 2001; Howieson et al., 2003).

Influenza virus survival exhibited a canonical dip between 40% and 80% RH in many studies (Harper, 1961; Hemmes et al., 1962; Lowen et al., 2007; Yang et al., 2012; Noti et al., 2013). For nearly all cases, virus survival declined relative to increased length of exposure. The review by Yang and Marr (2012) hypothesized that changes of pH within the aerosol, induced by evaporation, may trigger conformational changes of surface glycoproteins of enveloped viruses, leading to a decrease in viral infectivity.

In addition, low humidity does not cause thermal discomfort in terms of thermal sensation or how one feels thermally as long as the temperature is suitably adjusted for the humidity effect (Nevins et al., 1966; Fang et al., 1998; Sunwoo et al., 2006a; Sunwoo et al., 2006b). There is a large body of literature that quantifies the effect of humidity on heat stress at higher activity. No clear dividing line exists between thermal stress and comfort, and that dividing line gets more

blurred the higher the activity level. The assumption can be made that low humidity greatly improves comfort for active individuals, but the literature contains few, if any, data on the topic since studies conducted with minimal, sedentary activities cannot be appropriately extended to higher activity levels.

This literature review also identified some challenges and unanswered questions regarding the effects of low humidity. One of the significant challenges of determining the effects of low humidity on pathogens is that viruses and bacteria are constructed with lipid and non-lipid envelopes, so conclusions from one pathogen cannot be applied to all viruses or bacteria. This greatly increases the test matrices required to include various environmental conditions and species. Influenza has been studied significantly more than other viruses, and there are insufficient data regarding other viruses. Bacteria are constructed with different envelopes, usually termed Gram-positive or Gram-negative, but even in these subcategories, the behavior at low humidities varies (Theunissen et al., 1993). The review by Tang (2009) suggested that viruses with a lipid envelope survive longer at 20–30% RH at room temperature, while viruses with a non-lipid envelope survive longer at higher humidities, such as 70–90% RH. However, improved understanding of the effects of bacterial and viral construction on survival at low humidities is essential. Effects of low humidity and environmental conditions on anti-biotic resistant organisms, such as methicillin-resistant *Staphylococcus aureus* (MRSA), could be an interesting research opportunity. Knowledge of what environmental conditions, if any, reduce the spread of these anti-biotic resistant organisms would be beneficial for specific employment in hospitals and health care facilities.

Comparisons of laboratory studies of pathogens (Dunklin and Puck, 1948; Akers et al., 1966; Theunissen et al., 1993; Ko et al., 2000; Lowen et al., 2007; Yang et al., 2012; Lopez et al., 2013; Noti et al., 2013) posed a challenge in this analysis due to different lethality levels amongst organism types. For example, many studies reported a starting virus titer and percent survival as a function of time. However, if a study began with an initial titer of 10^8 PFU/mL, then a 0.01% viability would still correspond to a concentration of 10^4 PFU/mL. Although the percentage reduction seems impressive and desirable, 10^4 PFU/mL can be an infectious dose depending on the pathogen. Standardization of test conditions may improve comparison between studies. Memarzadeh (2012) noted in his review that it was “nearly impossible” to compare studies in the literature due to the unique study designs and conditions.

Health effects as a result of pathogens depend on the human host, the indoor environment (e.g. porous versus non-porous surfaces, RH, ventilation rates, number of people in the household, pets, and proximity to farm animals), particular pathogens that are endemic to an environment, and how those pathogens gain entry to the human host. Some pathogens require an acidic environment to undergo endocytosis, while others do not. Host response was not broadly considered in the literature. Ventilation also is a confounding variable on the effects of low humidity, as well as a lack of controlled human to human virus transmission studies; these conclusions were also drawn in the review paper by Memarzadeh (2012). Fewer studies considered airborne transmission or disease transfer through fomites (Lowen et al., 2007; McDevitt et al., 2010; Lowen and Steel, 2014). No studies identified in this review considered the host response in humans, which may be an important variable.

Although the data indicated that low humidity, mainly in cold air, does trigger asthma (Bundgaard et al., 1982; Kaminsky et al., 1995), the studies were conducted to determine the mechanism of exercise induced bronchospasm, and do not address the specific lower humidity limits. In addition, asthmatics are extremely susceptible to URTIs and LRTIs, where humidity is a factor for transmission and infection. Tradeoffs must be made to determine ideal indoor humidity conditions for asthmatics.

Any comfort effect of low humidity can be attributed to skin, eye, and mucous membrane irritation. At low humidities (breakpoint approximately between 20 and 30% RH) studies have suggested that evaporative tear losses increase and blink frequencies are higher in healthy eyes in a short term environment on the order of minutes to hours (McCulley et al., 2006; Sunwoo et al., 2006a; Wyon et al., 2006; Arciniega et al., 2011; Abusharha and Pearce, 2013). Reports of some discomfort and decreased performance of office tasks were also noted in the study by Wyon et al (2006). This study is addressed the effect of low humidity on performance and included four independent measures, all of which were impacted. Other studies did not address performance or productivity measures. However, throughout all studies, no information was obtained regarding long-term effects of low humidity on vision, eye comfort, or eye health. Increased skin discomfort and itching was observed at ultra-low humidity levels (1.5–2.5% RH) and mild skin discomfort effects were observed for healthy patients in humidity ≤ 30% RH. The data suggest that initial TEWL was when a subject entered a low humidity condition, after which the skin adapted (in a time scale of 30–60 minutes) in order to conserve water in the short term.

Few conclusions can be drawn regarding the IEQ literature. Results on the effects of RH on VOC emissions from building materials were inconclusive, and depended on the type of material and type of VOC. Emissions from materials may or may not change with changes in temperature and humidity. In general, increases in temperature and humidity decreased the perceived quality or acceptability of the air (Fang et al., 1998; Fang et al., 1999). In the study by Cain et al. (Cain et al., 2002), dilution (concentration) and temperature had far stronger effect than RH on TVOC emissions and perceived air quality.

Although a few studies have examined interactions between the effects of low humidity and environmental pollutants on human subjects (Norbäck and Edling, 1991; Nordström et al., 1994; Fang et al., 1998), no strong dependencies have been found. Fang et al. (2004) reported an increase of fatigue, headache, and difficulty thinking at low levels of temperature and humidity. In contrast, Norback et al. (1990) did not observe a correlation between room temperature [20–23 ^{o}C (68–73.4 ^{o}F)] and humidity (20–47% RH) with sick building syndrome symptoms. Fiedler et al. (2005) exposed women to brief (three hour) mixtures of VOCs with and without ozone. No significant subjective or objective health effects were reported as a result of the short VOC exposure. Ozone was not strongly influenced by humidity (Weschler, 2006; Uhde and Salthammer, 2007). In the low humidity range, humidity was a secondary variable for ozone pollution and VOC emissions.

Several gaps were identified in the IEQ literature. Previous research focused on the root causes of sick building syndrome, and therefore has not directly established the lower limit for acceptable RH in connection with IAQ. Of the building materials tested, VOC emissions varied greatly between materials and conditions; additional testing may be required for more information. Ozone was not strongly influenced by humidity (Weschler, 2006; Uhde and Salthammer, 2007). Studies that addressed particulates and particulate generation were conducted at higher humidities (Hitzenberger et al., 1997), and it is unclear what effects, if any, lower RH would have on particulates.

5.2 Human subjects and population

Table 3 details the ages of human subjects in health, comfort, and IEQ tests. A few studies considered children under the age of 18, using surveys or environmental sampling in the homes of children with asthma (Infante-Rivard, 1993; Ezeamuzie et al., 2000; Kovesi et al.,

2007) and dust mite allergies (Munir et al., 1995). Smedje et al., 1997a surveyed Swedish teenagers (13–14 years old) and took measurements in public school classrooms. Jaakkola et al., 2014 and Makinen et al., 2009 studied Finnish military conscripts, aged 17–29. No studies conducted in controlled, environmental chambers considered the effects of low RH on children or adolescents. A few studies used a large number of subjects of various ages or large data sets spanning multiple age groups (Ezeamuzie et al., 2000; Davis et al., 2012). Ezeamuzie et al. (2000) studied asthma and allergies in more than 600 subjects in Kuwait. Davis et al. (2012) examined the impact of weather on pneumonia and influenza mortality deaths in the NYC metro and included a wide age range.

For controlled studies particularly in comfort, university students were the predominant subject group, as shown in Table 3. The study by Sunwoo et al. (2006b) was the only identified laboratory study which considered the elderly and included eight young men (average age 22) and eight elderly men (average age 72). Measurements of skin and eye irritation, such as TEWL and blink rate, were similar between the two age groups. At very low humidity (10% RH), mucociliary clearance measured by SCT method decreased in elderly group as compared to young men, while they showed no difference at 30% and 50% RH. Although interesting, these data represented a 50 year age difference, yet included a small sample size and only male subjects. Further studies are required to increase the knowledge for the elderly population.

In addition, many field studies were conducted by researchers on Scandinavian populations (e.g., Denmark, Finland, Norway, and Sweden) as shown in Table 4. In these northern climates, indoor humidities can be 10–20% RH during winter heating seasons. Do these populations acclimate to low humidity? It would be interesting to know whether more diverse populations have the same sensations of dryness and responses to low humidity.

5.3 Ventilation rates and air velocity

From this literature survey, ventilation rates and air velocity emerged as confounding variables that interact with humidity; interaction is an area for further exploration. Comparison with regard to ventilation type is challenging because it is not reported by all studies. Building types are tabulated in Table 4 for field studies which conducted on-site building measurements, and single-family homes and offices were the most commonly studied buildings. Studies of homes often included a range of ventilation types (i.e., natural ventilation, ventilation by exhaust fan,

and mechanically ventilated), with a few studies regarding dust mites in homes explicitly including natural ventilation (Munir et al., 1995; Sundell et al., 1995; Arlian et al., 2001).

One review (Seppänen and Fisk, 2004) suggested that ventilation impacts building conditions such as air quality, asthma, and allergies. Kovesi et al. (2007) emphasized the importance of adequate ventilation rates for Inuit children at risk for respiratory infections and asthma. Several studies emphasized the interaction between dust mite survival and ventilation (Harving et al., 1993; Munir et al., 1995; Sundell et al., 1995); ventilation has been postulated to alter humidity in the micro-environment, thereby affecting dust mite survival.

A few studies have addressed the effects of ventilation on pathogens. Yang and Marr (2011) modeled aerosolized droplets (1–100 μm), with application towards influenza A airborne transmission. They considered ventilation rates of 1 ACH and 10 ACH for a wide relative humidity range, 10–90% RH, and observed that higher ventilation rates may cause larger droplets to settle faster, while ventilation and virus inactivation were more important for droplets less than 5 μm. Gorny et al. (2002) and Pasanen et al. (1991) found that increased air velocity increased fungal aerosolization.

Several studies addressing IEQ included ventilation as a parameter in surveys or environmental chamber testing (Smedje et al., 1997b; Wolkoff, 1998; Fang et al., 2004; Wyon et al., 2006; Strøm-Tejsen et al., 2007). Wyon et al. (2006) and Fang et al. (2004) did not find strong relationships between ventilation rates and perceived air quality. However, in a survey of workers in 38 Swedish schools, Smedje et al., 1997b noted a possible influence of mechanical ventilation on perceived air quality at low humidity levels. Wolkoff (1998) measured VOC emissions from common building materials and noted an effect of air velocity dependent on the emission mechanism. Strøm-Tejsen et al. (2007) examined the tradeoffs between humidity and contaminants in an aircraft mockup; total ventilation rates were maintained at 200 L/s (424 cfm), with varying amounts of fresh outdoor air, resulting in humidities of 7-28% RH at an air temperature of 23 ^{o}C (73.4 ^{o}F). Decreasing the percentage of outside air to increase humidity did not have a beneficial effect and, if anything, decreased overall acceptability of the environment due to increased contaminants.

5. Exposure times

The majority of laboratory studies with human subjects were of short duration, typically three hours of exposure to conditions in an environmental chamber, or several weeks or months

for environmental surveys. Due to the brief duration of most studies in controlled conditions on human subjects, extrapolations could not be made towards long term exposure to low humidity conditions. Studies on eye irritation by Abusharha and Pearce (2013) and Laviana et al. (1988) noted time as an important variable; studies were 1 hour and 10 hours long, respectively. Work by de Dear et al. (1989) examined the effects of humidity transients as subjects moved between 20% RH and 80% RH chambers at 23.3 ^{o}C (74 ^{o}F). They noted that effects of humidity transients on thermal comfort could last up to 90 minutes. Andersen et al. (1974) studied male university students (N=8) in an environmental chamber for a total of 125 hours; this was, by far, the longest controlled, environmental chamber study located in this literature review.

Some evidence suggests that metrics, such as skin water loss, adapt with time. In the study by Sunwoo et al., 2006a, at 10% and 30% RH, TEWL increased after thirty minutes and then stabilized. Indications of skin adaptation with time were evident in the ultra-low humidity studies (Chou et al., 2005; Chou et al., 2007) that spanned years. The question of human adaptation to low humidity is interesting and warrants future study because adequate information regarding the long-term effects of low humidity does not exist in the literature.

6. Conclusions and future work

Nearly 600 papers were identified as part of this literature survey, and of those papers, approximately 70 papers were discussed in detail. In general, papers included in this review comprised of controlled studies which included new data, and reported temperature and low humidity (RH$\leq$40%). The focus of this literature survey was on healthy human subjects, although animal models were considered relating to disease transmission. Papers were identified pertaining to health, comfort, and IEQ.

The effects of low humidity on asthma, dust mites, eye and skin dryness, and IAQ are some aspects of health, comfort, and IEQ were identified and discussed in this literature survey. Based on available studies, trends were discussed in these broad categories regarding the effects of low humidity. However, few studies identified the direct benefits or consequences of increasing RH by 10%, for example. In addition, for building occupants, what are the appropriate weightings of the comfort, health, and IEQ categories? There are inherent tradeoffs, such as lowered humidity reduces dust mite allergens but drier mucosa and increased virus survival impact asthmatic patients. In addition, ventilation rates and time had a confounding effect on low humidity. Appropriate weightings of these categories and parameters are open questions for

further inquiry and discussion. Opportunities for future work depend on the building type and specific priorities to optimize (e.g., productivity, decreased virus transmission, health benefits, etc.).

A majority of studies involving human subjects conducted tests at a limited number of humidity levels, often two or three. Test matrices understandably are limited due to cost and time required for testing. However, the thermal comfort work by Nevins et al. (1966) is a notable exception, as it included a test matrix of 72 temperature and humidity combinations. As a result of limited humidity levels presented in the studies, determination of acceptable or unacceptable conditions is difficult because studies lack good resolution between humidity levels.

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Nomenclature

ACH	air changes per hour
IAQ	indoor air quality
IEQ	indoor environmental quality
HDM	house dust mites
LRTI	lower respiratory tract infection
RH	relative humidity
SCT	saccharin clearance time
SET^*	standard effective temperature
TEWL	transepidural water loss
URTI	upper respiratory tract infection
VOC	volatile organic compound

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List of Tables

Table 1 Keywords for keyword searches

Effects of low relative/absolute/specific humidity on:	Search terms
Comfort	Skin dryness, Thermal comfort, Comfort, Eye irritation, Static electricity
Health	Health effects, Bacteria, Virus, Influenza, Pneumonia, Asthma, Allergy, Eukaryotes, Eukarya, Metagenomics, Microbiome, Microbes, Microbial, Mites, Infections, Respiratory infections, Fungal Fungi, Allergic rhinitis, Physiological effects, 16s RNA
IEQ	Ozone generation, Particulate level, Particulate generation, PM2.5, bioaerosol
Population	Adolescents (13–18), Adults, Adults over 65

Table 2 Key papers for further literature search

	Category	Key paper(s)
Comfort	Eye irritation	(McCulley et al., 2006)
	Skin dryness	(Sunwoo et al., 2006a)
		(Reinikainen and Jaakkola, 2003)
	Thermal Comfort	(Berglund, 1998)
Health	Asthma	(Bundgaard et al., 1982)
		(Strauss et al., 1978)
	Bacteria	(Dunklin and Puck, 1948)
	Influenza	(Shaman et al., 2011)

	Mite	(Howieson et al., 2003)
	Pneumonia	(Theunissen et al., 1993)
	Virus	(Akers et al., 1966)
Population	Elderly	(Sunwoo et al., 2006b)
IEQ	Ozone generation	(Grøntoft and Raychaudhuri, 2004)
	Particulate generation	(Hitzenberger et al., 1997)
	IAQ	(Fang et al., 2004)
		(Nordström et al., 1994)
		(Wolkoff and Kjærgaard, 2007)

Table 3 Subject ages for tests in health, comfort, and IEQ

Category	Paper	Children (0-13)	Adolescents (13-18)	University students only	Adults (18-65)	Elderly (>65)
Asthma/respiratory	(Andersen et al., 1974)			X		
	(Bundgaard et al., 1982)				X	
	(Charpin et al., 1988)				X	
	(Ezeamuzie et al., 2000)	X	X		X	X
	(Infante-Rivard, 1993)	X				
	(Kovesi et al., 2007)	X				
	(Smedje et al., 1997a)		X			
Dust mites	(Munir et al., 1995)	X				
Viruses/ bacteria	(Barreca and Shimshack, 2012)				X	
	(Davis et al., 2012)	X	X		X	X
	(Jaakkola et al., 2014)		X		X	
	(Mäkinen et al., 2009)		X		X	
Comfort	(Abusharha and Pearce, 2013)				X	
	(Andersen et al., 1974)			X		
	(Arciniega et al., 2011)				X	
	(Chou et al., 2005)			X		
	(de Dear et al., 1989)			X		
	(Fang et al., 1998)			X		
	(Laviana et al., 1988)			X		
	(McCulley et al., 2006)				X	
	(Nevins et al., 1966)			X		
	(Nordström et al., 1994)				X	
	(Reinikainen et al., 1991)				X	
	Sunwoo et al. (2006) (Sunwoo et al., 2006a)			X		
	Sunwoo et al. (2006) (Sunwoo et al.,			X		X

	2006b)					
	(Tsutsumi et al., 2007)				X	
	(Wyon et al., 2006)			X		
IEQ	(Cain et al., 2002)				X	
	(Fang et al., 1998)			X		
	(Fang et al., 1999)			X		
	(Fang et al., 2004)			X		
	(Fiedler et al., 2005)				X	
	(Kay et al., 1990)				X	
	(Norbäck et al., 1990)				X	
	(Reinikainen et al., 1992)				X	
	(Smedje et al., 1997b)				X	
	(Sundell and Lindvall, 1993)				X	

Table 4 Building types for field studies

Study	Category	Building type and number of buildings	Location
(Kovesi et al., 2007)	Asthma	Single family homes (*N*=49)	Canada
(Munir et al., 1995)	House dust mite	Single family homes (*N*=98) and apartments (*N*=28)	Sweden
(Sundell et al., 1995)	House dust mite	Single family homes (*N*=30)	Sweden
(Arlian et al., 2001)	House dust mite	Homes (*N*=71)	United States
(Reinikainen et al., 1991; Reinikainen et al., 1992; Reinikainen and Jaakkola, 2003)	Skin irritation and IEQ	Multi-story office building (*N*=1)	Finland
(Nordström et al., 1994)	Skin irritation	Four hospital units in two hospitals (*N*=2)	Sweden
(Chou et al., 2005; Chou et al., 2007)	Skin irritation	Laboratory (*N*=1)	Japan
(Norbäck et al., 1990)	IEQ	Workplaces with more than 10 employees (*N*=11)	Sweden
(Sundell and Lindvall, 1993)	IEQ	Office buildings (*N*=210)	Sweden
(Smedje et al., 1997b)	IEQ	Schools (*N*=38)	Sweden

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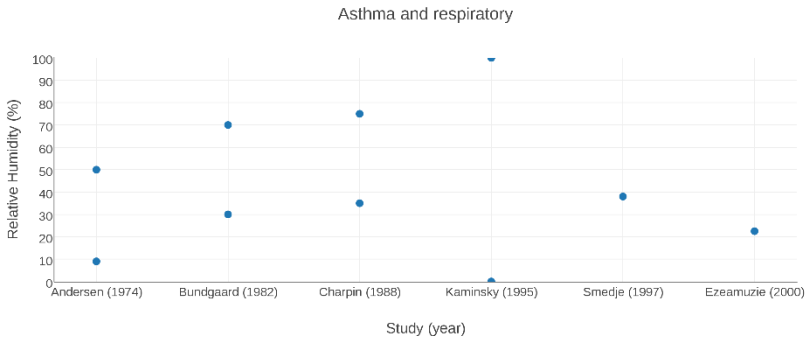
a)



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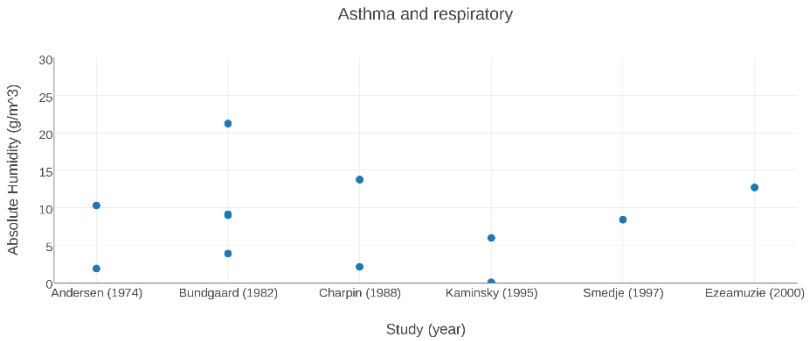

Figure 1 Test conditions for asthma papers related to a) relative humidity and b) absolute humidity

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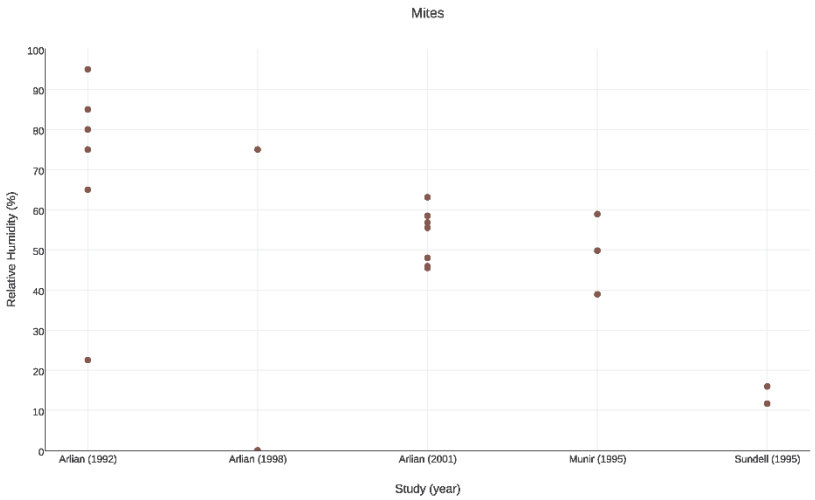

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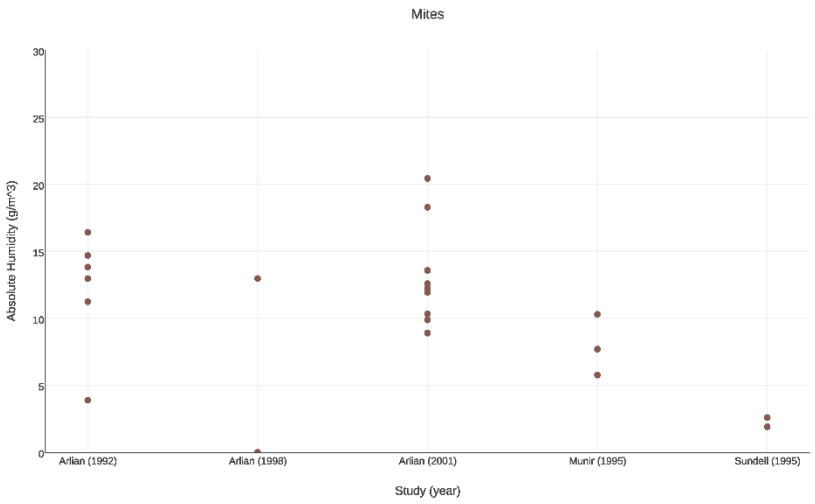

Figure 2 Test conditions for dust mite papers related to a) relative humidity and b) absolute humidity

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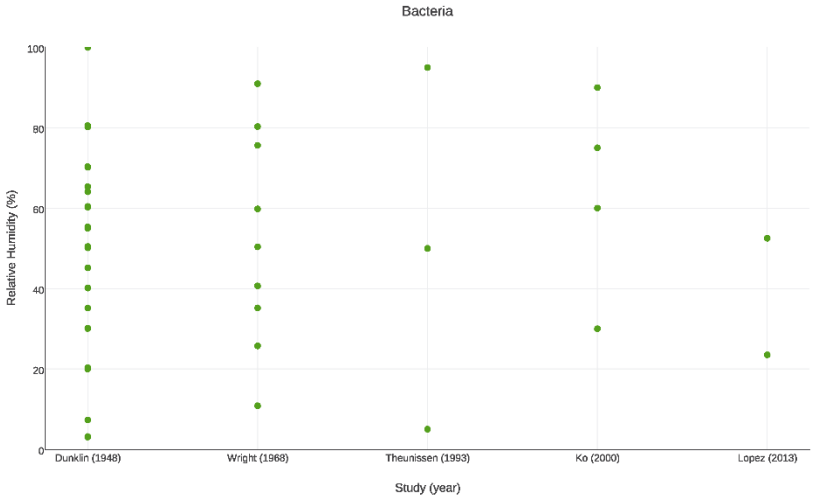

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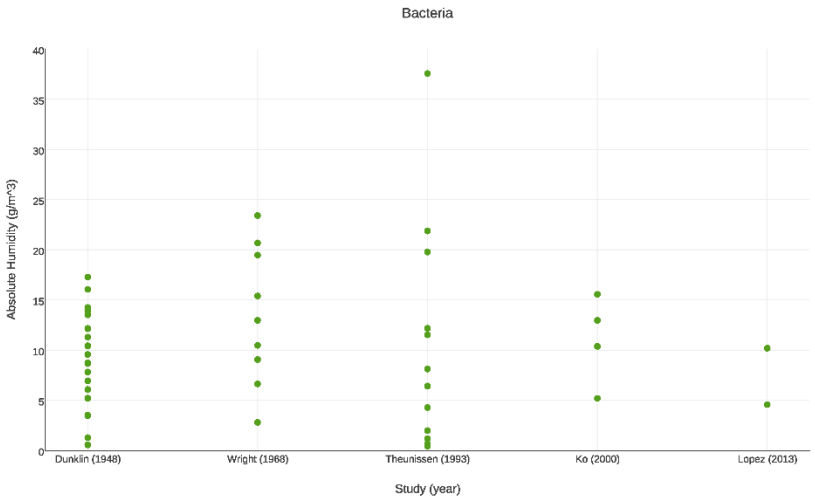

Figure 3 Test conditions for bacteria papers related to a) relative humidity and b) absolute humidity

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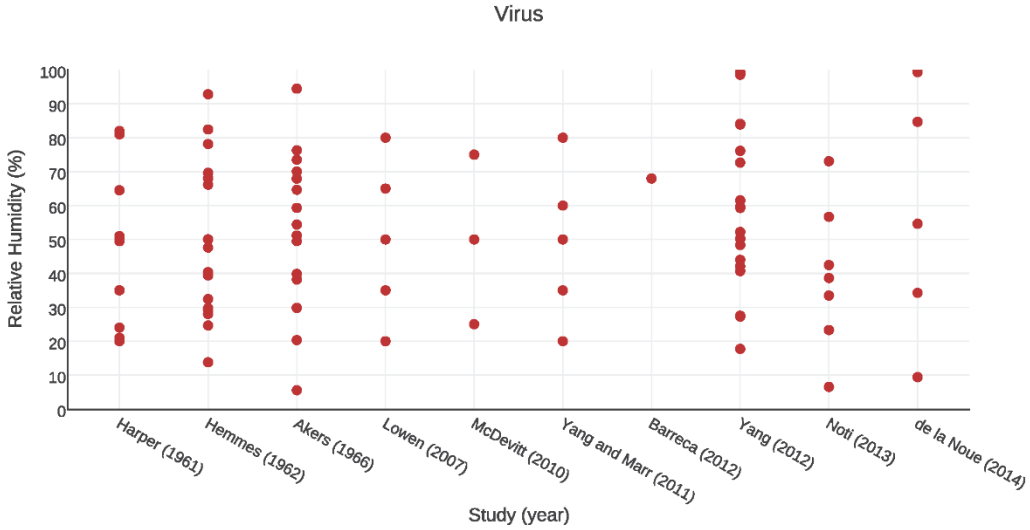

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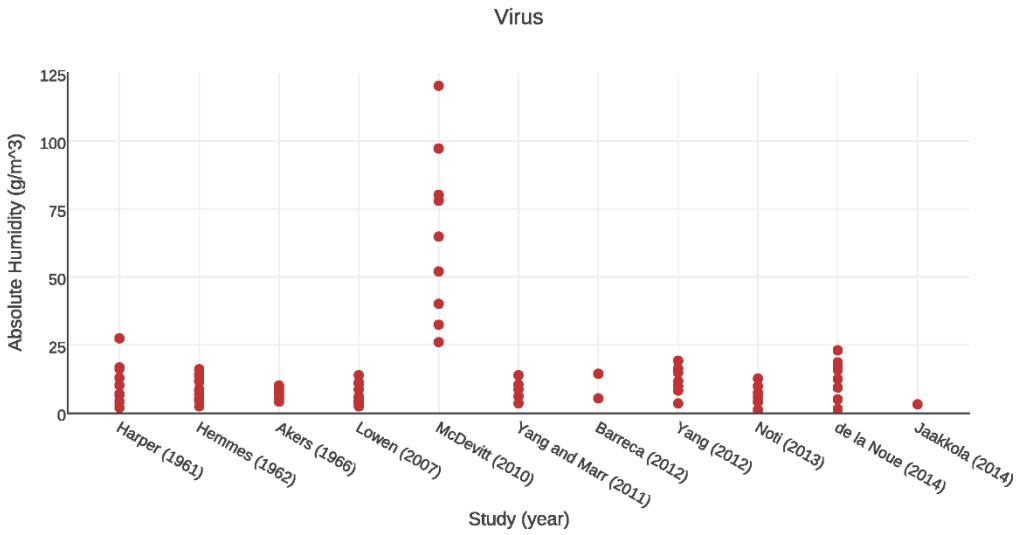

Figure 4 Test conditions for virus papers related to a) relative humidity and b) absolute humidity

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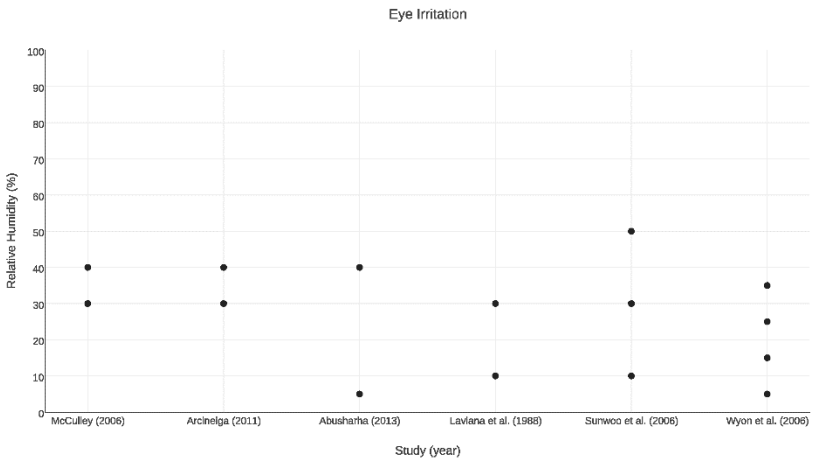

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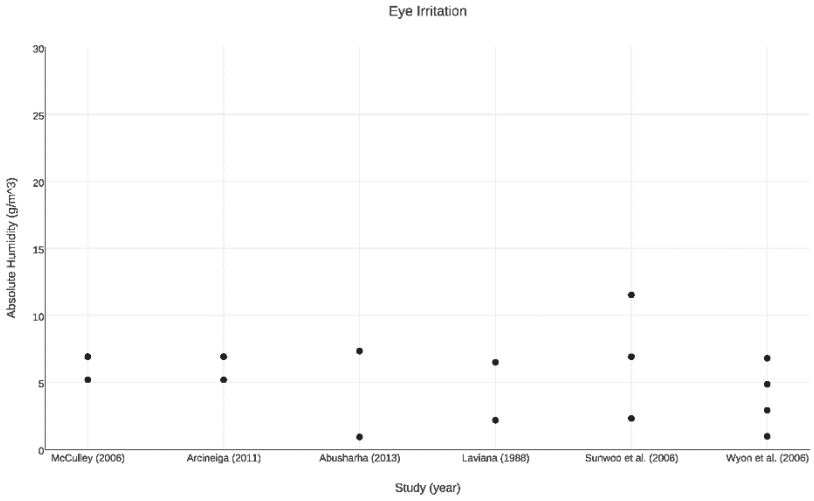

Figure 5 Test conditions for eye irritation papers related to a) relative humidity and b) absolute humidity

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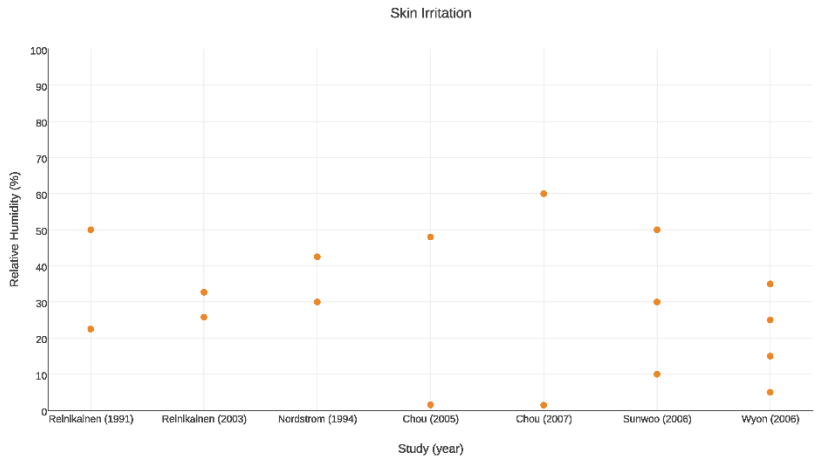

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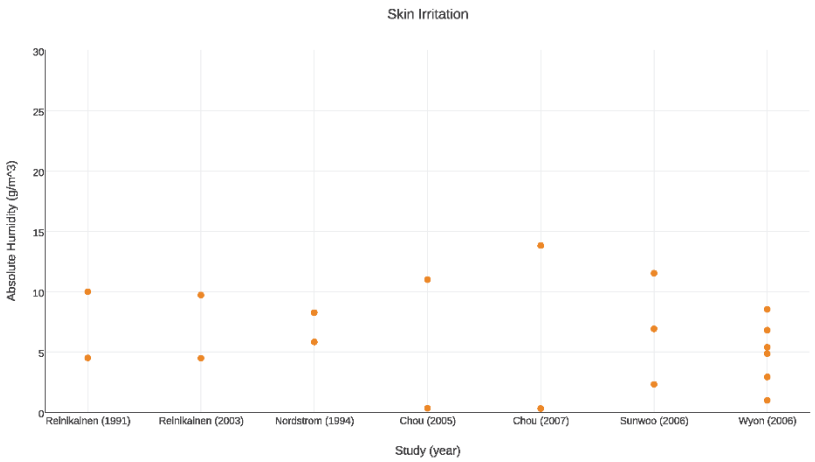

Figure 6 Test conditions for skin dryness papers related to a) relative humidity and b) absolute humidity

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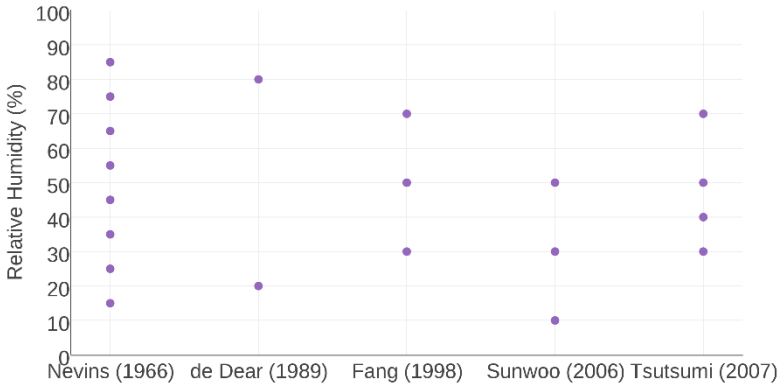

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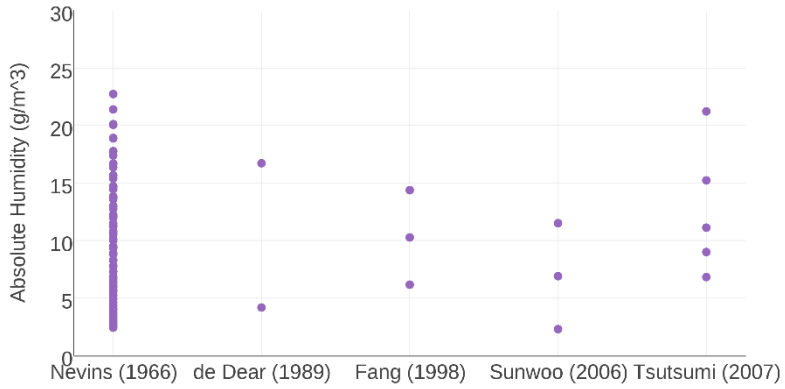

Figure 7 Test conditions for thermal comfort papers related to a) relative humidity and b) absolute humidity

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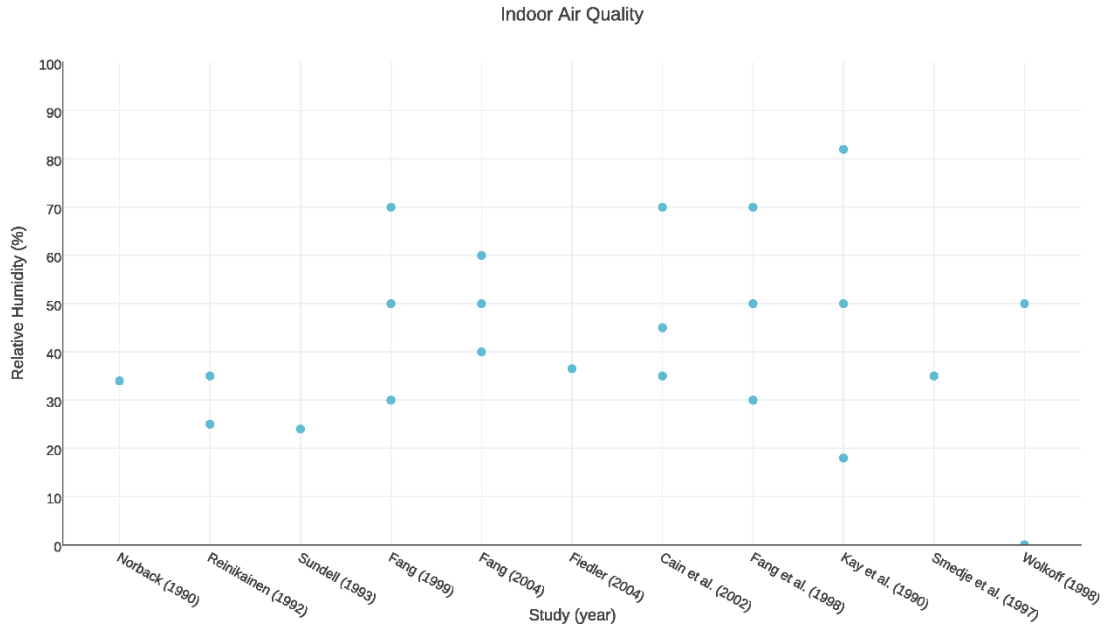

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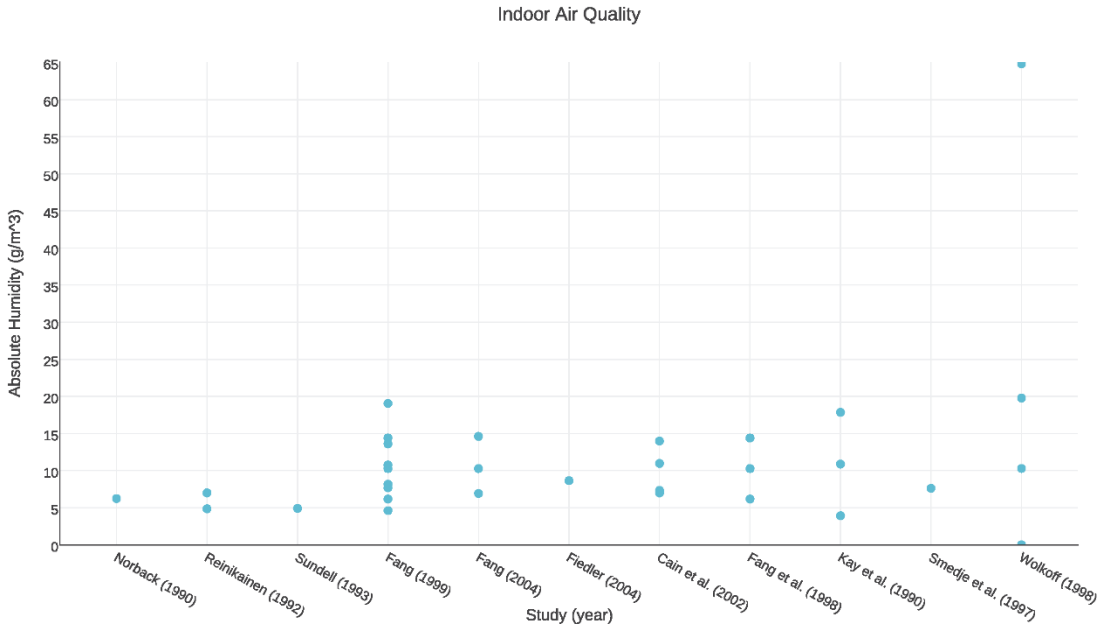

Figure 8 Test conditions for IEQ papers related to a) relative humidity and b) absolute humidity

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