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Abstract

The NZ standard "Ventilation for Acceptable Indoor Air Quality" (NZS 4303, 1990) recommends a CO_2 level of 1000 ppm or less. The 2017 guideline published by the NZ Ministry of Education has recommended that a classroom user should not be exposed to a CO_2 level above 1500 ppm. What does this mean for a primary school teacher actively engaged in educating and managing a classroom of 40+ children? This paper presents data collected from ten primary schools (Years 1 to 6, ages 5 to 12) in New Zealand (NZ). Using the ICONE score, the 28 classrooms surveyed were characterised according to their air stuffiness. ICONE is a communication tool for occupants, which considers the frequency and intensity of carbon dioxide (CO_2) concentration levels around stated threshold values. The index can then be expressed between 0 and 5, which correspond to an air stuffiness gradient of 0-none, 1-low, 2-average through 5-extreme. The results of our study show that 43% of the NZ classrooms report an index between 3-high and 5-extreme. Using an electroencephalogram to estimate student's cognitive performance, the results of a pilot study show the brain map of a participant performing a typing test under two different levels of air stuffiness (0 and 4). There is visual evidence of how the alpha brainwaves are responding.

A key novelty of our study is the strategic research relationship that has continued to develop with the NZ Ministry of Education, leading to more advanced and innovate research opportunities.

1. Introduction

In 2017, the New Zealand Ministry of Education (NZMoE) released a series of guidelines to assist principals and teachers in understanding the importance of a school's internal environment. When schools submit their five-year maintenance for funding or 10-year property plan, they are established upon these guidelines. The guidelines also support assessing the attainment of performance of existing teaching spaces to measure 'fitness for purpose', which is a key target of the 2030 NZMoEs' Achieving Quality Learning Environment (QLE) Strategy.

NZMoE requires occupants to be able to identify and control classroom temperature and carbon dioxide (CO_2) levels (Ministry of Education, 2017). The QLE guidelines state that the teacher should "appoint student monitors in each learning space … for monitoring CO_2 levels … of each school period, setting the windows/vents…" (Ministry of Education, 2017, p.21). The feasibility of this has not been tested in NZ.

The two research objectives for our study are: 1) develop a tool which will help school administrators write meaningful reports on the indoor air quality (IAQ) of their learning environments in order to meet NZMoE requirements; and 2) to provide teachers using the learning spaces with a tool which provides expressive, easy to use, instant feedback on CO_2 levels.

In 2018, the NZMoE outlined a reform on school property to ensure all students and teachers can learn and work in quality environments that will support their success (Ministry of Education, 2018). At this time, the NZMoE property estate consisted of approximately 2,100 state schools. 57% of these classrooms are more than 40 years old, of which "several hundred" (Cowlishaw, 2018) do not meet the current standards for temperature, humidity, air quality, acoustics and lighting. The estimated cost to address this is NZ$160 million (Ministry of Education, 2018). Therefore, approximately 10% (StatsNZ, 2018) of the total NZ population, the next generation (and their teachers) are spending between 65 and 90% (Annesi-Maesano et al., 2013) of their waking time indoors at school often in unsatisfactory, potentially harmful, working environments.

Bluyssen (2016), reported that children are more susceptible than adults to the adverse health effects of poor IAQ. This is in part due to their higher metabolic rate, which demands increased oxygen availability and therefore, higher ventilation rates per minute. Besides the negative health effects (headaches, dry cough), poor IAQ also impacts students comfort, concentration, cognitive function and development (Bluyssen, 2009; WHO, 2007). All of these IAQ and environmental variables ultimately impact academic performance (Mendell & Heath, 2005; Stafford, 2015). Indeed Sunyer et al. (2015) reported that 7-to 10-year old children attending schools exposed to high levels of traffic-related air pollution had slower cognitive development than children attending lower polluted schools. Similarly, Mendell et al. (2013) observed that high ventilation rates in classrooms improve children's health and school attendance.

Optimal ventilation is key for the holistic design of any quality indoor environment. It is possible to provide ventilation through natural, mechanical or mixed natural/mechanical ways. The ventilation method employed is dependant upon several factors, ranging from occupancy density, acoustics and other site-specific requirements.

A study undertaken by Luther & Atkinson (2012), found that CO_2 concentration levels were above 2,700 ppm in classrooms in Australia due to inadequate ventilation. The Schools Indoor Pollution and Health Observatory Network in Europe (SINPHONIE), undertook a study of 114 schools in 23 European countries, found that 86% of ventilation rates were less than the desired value of 4 L/sec per child (Csobod et al., 2014). In a NZ study, ventilation rates were found to be 16 times lower than the recommended value of 8 L/sec per person specified in Standards NZ 4303:1990 (Wang et al., 2017a). A local newspaper headline in NZ read “Hey Teachers, leave them *(sic)* windows open” Harvie (2018), in response to the research findings.

Seppänen & Fisk (2004) suggest that controlling ventilation is equivalent to controlling CO_2 concentration levels. According to Carrer et al. (2018), CO_2 is the most used indicator to estimate ventilation efficiency. A defining factor of the ventilation conditions within a given space depends on the nature of the space, time, room volume, number of people present and their exhalation rate of CO_2 and several other factors. Since 2017, fifteen primary schools have closed in NZ (Ministry of Education, 2018). These closures have put additional pressure on already limited classroom resources. Furthermore, as CO_2 is a dense gas and tends to concentrate at lower elevations, it is again the younger children that are more vulnerable. Jurelionis & Seduikyte (2008), state that high-density classroom occupation challenges the possibility of maintaining a good IAQ through adequate ventilation, without additional interventions.

McIntosh (2011), reported that approximately 90% of NZ classrooms are dependent on natural ventilation. This was supported by a comment published by BRANZ “NZ schools are, in most cases, designed to provide ventilation through opening windows” (Ministry of Education, 2017, p.7). Due to the high capital, energy and maintenance costs associated with conventional mechanical ventilation systems, many NZ schools are unable to afford mechanical ventilation and must rely on teachers opening windows and doors. However, a survey undertaken in 40 Auckland schools showed that only 40% of teachers open windows to let in fresh air during winter (Gully, 2015; Liaw, 2015).

Low ventilation rates in classrooms can lead to a build-up of CO_2 that could impact on children’s health, wellbeing and performance.

2. SKOMOBO – The SKOoL MOnitoring BOx

Investigating IAQ in classrooms is a substantial concern. As the environment can differ from classroom to classroom, these need to be monitored individually. Commercial IAQ monitoring equipment can cost upwards of NZ$2,500 (Wang et al., 2017b) per unit, and will be unaffordable for schools.

Developments in low-cost sensor research, remote logging and data transmission equipment have opened up new horizons for air quality monitoring and better built environment management. An IAQ monitoring solution has been developed at Massey University NZ, named SKOMOBO. SKOMOBO is a low-cost, low power consumption, indoor environment monitoring device (Wang et al., 2017b). The device is approximately 100 x 100 x 100 mm and monitors, temperature, relative humidity, particulate matter ($PM_{2.5}$ and PM_{10}), carbon dioxide (CO_2) and people motion. The CO_2 sensor used (Figure 1 below) is a SenseAir K30 model (Weyers et al., 2017). This model is part of the Non-Dispersive Infra-Red CO_2 sensors, which means that the amount of infrared light absorbed is proportional to the concentration of CO_2 in the enclosure (Senseair, n.d.).

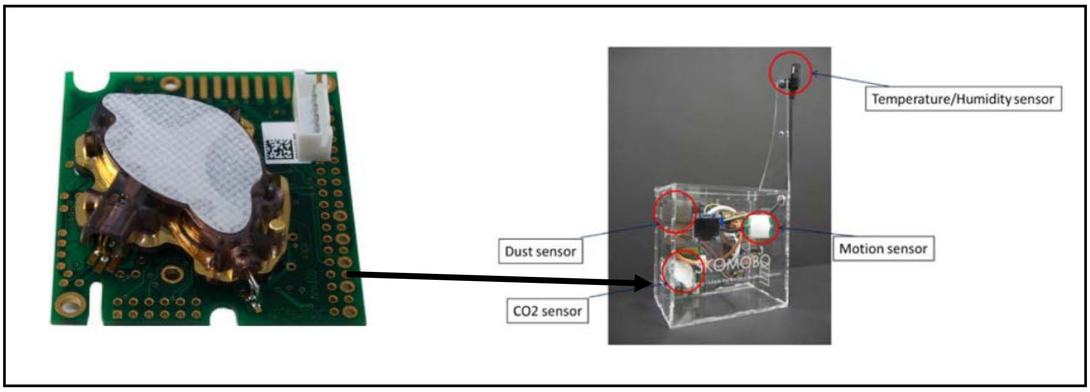


Figure 1: Non-Dispersive Infra-Red CO_2 sensors (Left) and SKOMOBO Platform (Right)

SKOMOBO provides a tool that can document the IAQ of classrooms. It captures ongoing evidence so that the indoor environment can be better researched and understood, ensuring healthy learning spaces can be provided. SKOMOBO testing shows a high correlation with their commercial counterparts (Wang et al. 2017b).

Data reported here are from ten SKOMOBO platforms deployed in September 2017. The schools used are located on the East coast of NZ, (North Island) and the remaining eight on the South Island, as depicted in Figure 2 below. Schools were selected to provide a mix of demographics and school decile rating as well as climate and building conditions.

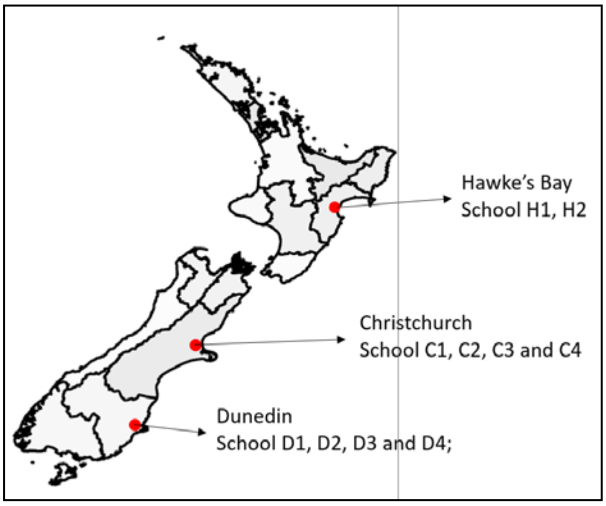


Figure 2: Location of ten primary schools in New Zealand

The ambient temperature during weekday school hours (9 am – 3 pm) in each region for the different seasons is detailed in table 1. The National Institute of Water and Atmospheric Research (NIWA) has 600 climate stations around NZ. The ambient air data can be accessed using the CliFlo online database.

Table 1: Mean (standard deviation) ambient temperature (ºC) during weekday school hours (not including term break) in each region for each season

Region	**Latitude**	**Spring**	**Summer**	**Autumn**	**Winter**
Hawke's Bay	39.1090	16.79 *(3.26)*	23.67 *(3.24)*	18.08 *(4.78)*	11.99 *(3.31)*
Christchurch	43.5321	15.19 *(4.32)*	20.41 *(5.02)*	14.79 *(5.56)*	9.25 *(3.05)*
Dunedin	45.8788	12.93 *(3.48)*	17.33 *(4.08)*	12.99 *(4.75)*	8.5 *(2.53)*

As is evident, it would be counter-intuitive for teachers to open windows in winter to let in the fresh outside air with such cold ambient temperatures. Again reinforcing the research conducted by both Gully and Liaw in 2015.

3. Air Stuffiness Index for Schools

As mentioned previously, CO_2 is a bio-effluent from metabolic production and is considered a good indicator to estimate ventilation, or for the layperson - air stuffiness. Teachers need guidance on the interpretation of CO_2 levels. Asking them "how well ventilated their space" is when there is no mechanical ventilation is meaningless. Providing them with a visual indicator showing them they need to ventilate the room, will add value. This can be done using a scale points systems or traffic light method.

In a study conducted by the French CSTB, researchers observed that when teachers were provided with evidence of their classroom air stuffiness levels, teachers systematically changed their classroom ventilation management. This initial research led to the development of a stuffiness index, "ICONE" (Indice de CONfinement d'air dans Les Ecoles), which translates to "air stuffiness index for schools".

The air stuffiness level is presented as an index and ranges from 0 (sufficient ventilation) to 5 (poor ventilation), as reported in Table 2. A score of 0 is the most favourable and infers that the CO_2 levels are always below 1000 ppm. A score of 5 corresponds to extreme air stuffiness, inferring that CO_2 levels are above the maximum threshold for the entirety of children occupancy time.

In accordance with the NZMoE guidelines, occupied learning spaces are expected to have "adequate ventilation to provide a minimum IAQ range between 1000 - 1500 ppm CO_2 (or less) over the school day" (Ministry of Education, 2017, p.5). However, an average of 1200 ppm or lower is required. The maximum peak concentration should not exceed 3000 ppm during the teaching day, and at any occupied time, the occupants should be able to purge the concentration of CO_2 to 1000 ppm within 10 minutes (Ministry of Education, 2017, p.8). Table 2 has been adjusted to fit the NZ guidelines.

Table 2: Air stuffiness according to the ICONE index score

ICONE index score	*Frequence of CO_2 values (**France**)*	*Air stuffiness*	*Frequence of CO_2 values (**NZ**)*
0	100% CO_2 value < 1000 ppm	Fresh air (no air stuffiness)	100% CO_2 value < 1000 ppm
1	~1/3 values > 1000 but < 1700 ppm	Low air stuffiness	~1/3 values > 1000 but < 1500 ppm
2	~2/3 values > 1000 but < 1700 ppm	Average air stuffiness	~2/3 values > 1000 but < 1500 ppm
3	~2/3 values > 1000 but 1/3 > 1700 ppm	High air stuffiness	~2/3 values > 1000 but 1/3 > 1500 ppm
4	~2/3 values > 1700 ppm	Very high air stuffiness	~2/3 values > 1500 ppm
5	~100% CO_2 value > 1700 ppm	Extreme air stuffiness	~100% CO_2 value > 1500 ppm

Adapting the CSTB ICONE method to the NZ school data, we have estimated the stuffiness index (Figure 3) of 28 primary school classrooms. It is important to remember the air stuffiness index only reflects the quality of the air change during occupancy. It does not provide any information during unoccupied periods. The score for one classroom can then be compared with other similarly instrumented classrooms.

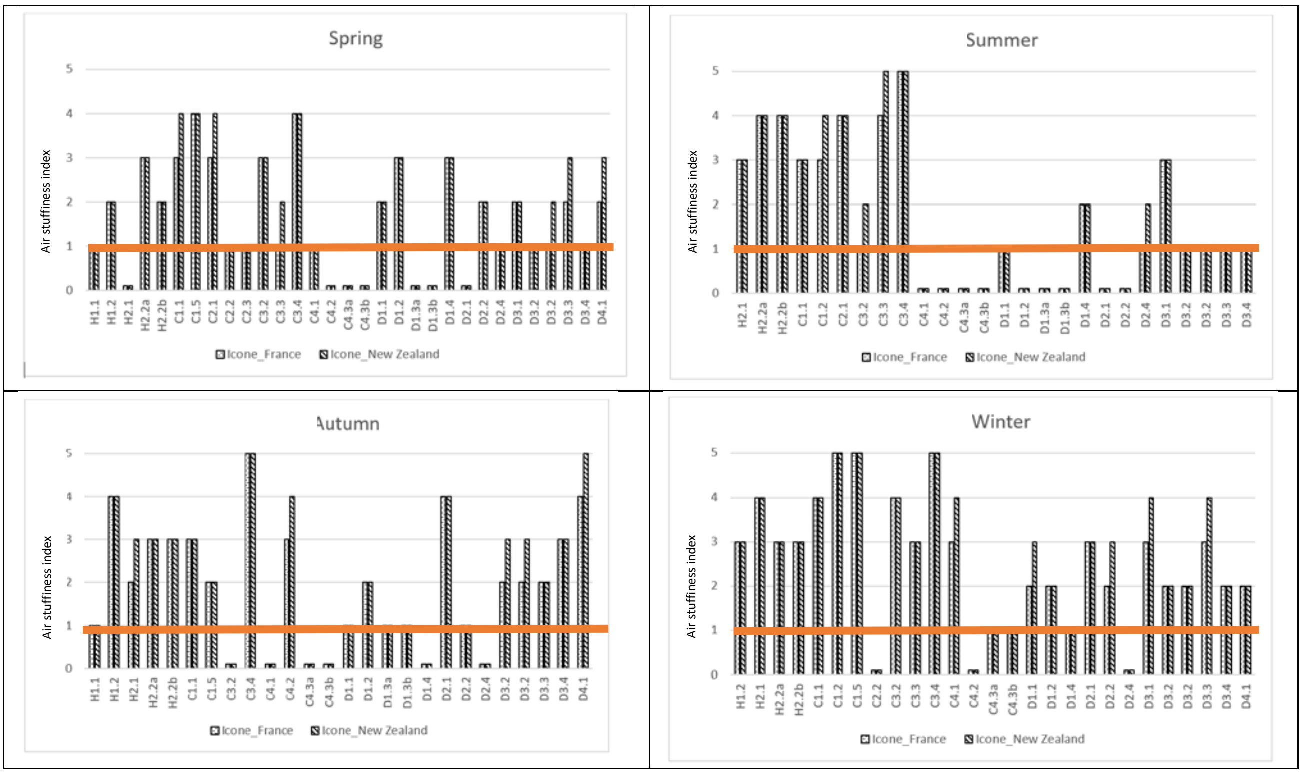


Figure 3: Air stuffiness of 28 New Zealand schools. (Below plain grey bar indicates an acceptable threshold level)

Consistent with the ambient temperature data previously presented, it is evident that the majority of teachers would be reluctant to open the windows in winter. Irrespective Dunedin surprisingly has a lower air stuffiness index overall compared with

Christchurch and Hawke's Bay. Comparatively, the students in Dunedin are exposed to average air stuffiness (two), followed by high air stuffiness (three) in their classrooms.

With regards to Christchurch (C) classrooms, C1.1 and C3.4 require consideration. For C1.1 during spring and winter, the ICONE air stuffiness index is very high (four), and during autumn and summer, it drops marginally too high (three). Is this perhaps due to a marginal increase in temperature? Or has the teaching pedagogy/curriculum changed? C3.4 registers extreme air stuffiness (five) for all but spring when it is very high (four). Classroom activity schedules and maintenance logs should be obtained to try to establish why this has occurred.

In Hawke's Bay (H), it is apparent that the majority of students were exposed to high air stuffiness (three) and very high air stuffiness (four). H2.2.a. consistently exposed students to high air stuffiness (three) autumn, spring and winter, with very high stuffiness (four) index in summer.

The impact of poor ventilation and an increase in CO_2 concentration levels (stuffiness) has been associated with up to a 20% increase in student absence from school (Shendell et al., 2004). Students who are absent from class, miss learning opportunities.

4. Impact of CO2 on the learning process – Preliminary data

As previously mentioned students spend most of their time in the classroom, second to their home (Guerra-Carrillo, Katovich, & Bunge, 2017). Healthy classroom environments not only improve students' performance and interpersonal relationships; it also enhances their psychological health (Willner, Gatzke-Kopp, Bierman, Greenberg, & Segalowitz, 2015). Research undertaken by Shaughnessy et al. (2008) on 5th-grade classrooms in 54 elementary schools, and Wargocki & Porras-Salazar (2017), on 100 5th-grade classrooms in 100 schools, shows there is a significance between CO_2, health and performance. Furthermore, CO_2 is now considered by researchers as a major factor for gastrointestinal, respiratory and cognitive disorders (Lu, Lin, Chen, & Chen, 2015; Thom, Bhopale, Hu, & Yang, 2017).

The next stage of the research will use an electroencephalogram (EEG), a non-invasive technique, to measure the participant's alpha brainwave in connection with the stuffiness score. It will do this in conjunction with cognitive performance parameters.

The alpha brainwave response is assumed to be the most significant due to its relationship with information processing. It is related to anticipation (Maltseva, Geissler, & Başar, 2000); motor behaviour (Pfurtscheller & Klimesch, 1992); memory processes (Klimesch, 1997) and primary sensory processing (Schürmann & Başar, 1994). Research undertaken by Yordanova & Kolev (1996) indicates that the alpha response frequency of 6-11-year-old children operates differently than that of adults. The most prominent increase in alpha wave occurs between 7-8 and 10-11-year-old children. This corresponds with the stages at which an increase in cognitive performance of children has been observed (Piaget & Cook, 2001). The reason our research will use cognitive performance and not academic performance is that academic performance is strongly associated with future achievement and teacher input (Nesayan, Amani, & Gandomani, 2019). Whereas cognitive achievement assesses a participant's current level of performance in (amongst others) attention span, processing speed, working memory and cognitive flexibility (Modrek, Kuhn, Conway, & Arvidsson, 2017).

The images below (Figure 4) are results from EMOTIV BrainVIZ, a real-time 3D visualisation software. They show the changes in the state of the brain of a participant performing a typing test (attention). The participant was in a sealed room with two other participants for 20 minutes. Two researchers were also present. The CO_2 levels were manipulated by the entry of participants only.

The image displays both the spatial properties (where in the brain the activity occurred); and temporal properties (what kind of activity it is). The pilot study recorded stress and focus.

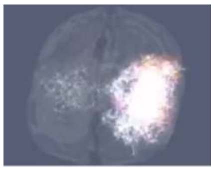
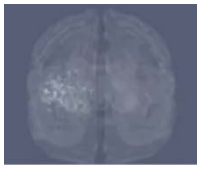
EEG scan under acceptable CO_2 levels		EEG scan under elevated CO_2 levels	
800 – 1000 ppm (ICONE 0)		1100 – 1500 ppm (ICONE 4)	
			
Normal Stress	Normal Focus	Elevated Stress	Loss of Focus

Figure 4: Brain map images of a pilot study participant

Preliminary results show that under fresh air conditions (ICONE 0) while performing the test, the participant experienced a minor, but normal, level of stress. Their response in the survey was "due to unfamiliar conditions". Their alpha brainwaves light up when performing the test (focus). However, once the room reached a very high stuffiness level (ICONE 4), and they performed the test again, their response to stress was elevated. Their feedback, however, on the survey was the opposite. They felt at ease as they knew what to expect. Their alpha activity is virtually non-existant while performing the test (loss of focus). Overall there was a 32% increase in error rate between performing the test with fresh air versus very high stuffiness levels. There was no change in the test parameters, so one could argue that there should have been a 'learned value'. Perhaps the error rate would have been higher if the test had been randomised.

Next, our study will look at recording temperature, relative humidity data, light and noise levels in the same primary schools. After that, participants will be exposed to these various conditions in our environmental chamber. They will be required to perform a series of cognitive tests, while the environmental factors change at a set rate. The objective is to ascertain the impact that the factors have on cognitive performance. It must be remembered however that no factor works in isolation so that these tests will be performed, initially on their own, then as a multivariate optimisation experiment. Which factor(s) have the greatest impact; this is what the teachers and designers need to know to optimise design solutions for classroom 'fitness for purpose' as well as ultimate academic outcomes. Teachers need to be able to focus their energies in class so that they can educate; designers need to know so that they can optimise the dollars spent.

The research will provide evidence-based research outputs to the New Zealand Ministry of Education on both summer and winter indoor environmental quality. It will also provide brain mapping evidence of various simulated scenarios during which we expect our children to be attentive in class.

The research will help show which factors the primary schools need to focus their efforts to facilitate them reaching their 2030 NZMoE quality learning environment target.

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