Perceived and measured indoor environment in educational buildings

Tuomo Ojanen [a], *Esa* Nykänen [b], *Teemu* Vesanen [c]

VTT Technical Research Centre of Finland Ltd,

[a] tuomo.ojanen@vtt.fi, [b] esa.nykanen@vtt.fi, [c] teemu.vesanen@vtt.fi .

Abstract. In educational buildings there is strong variation of the user-caused loads on indoor air during the working days. The challenge is to energy efficiently maintain comfortable indoor environment allowing good working and learning conditions for the building users. The objective was to define the main factors having effect on the user experience of indoor environment and to evaluate what range of measured factors are found comfortable in different building user groups. Three educational buildings representing different grades and one day care center were studied at least for a one-year period to find the main factors affecting the perceived indoor environment comfort in these spaces. Altogether 30 selected spaces were monitored, and perceived comfort of the users was collected through a novel real-time feedback system. The users could give their feedback concerning the perceived thermal comfort, humidity, air freshness and cleanliness, odours, lighting, noise and capability to work and learn. The feedback was based on the targets presented in the classification of the indoor environment [1] using Likert-scales [2] in questions. Each feedback of the experienced indoor environment condition had the space and time identification for the comparison with the corresponding monitored values. All the four sites had modern building technology systems. Only a weak correlation could be found between measured temperatures and the primary goal, i.e. good learning and working conditions. However, stronger correlation was found with the lighting, noise/acoustics, air freshness and humidity. With the humidity levels, both too low and too high levels affected the comfort. The effect of the total VOC-level on the comfort depended on the case - only in the day care center it had a strong negative effect. One relevant finding was that there was no difference between the user comfort in a case with full time ventilation compared to a case where the ventilation that was shut down during unoccupied hours to save energy. This paper presents the analysed findings for the measured and feedback data for these cases.

Keywords. Indoor air quality, indoor environment, educational buildings, schools, ventilation, learning conditions, working conditions
DOI: https://doi.org/10.34641/clima.2022.386

1. Introduction

Indoor environment has strong effect on the perceived working and learning capability. Educational buildings are quite demanding in that connection while the internal loads and user demand may vary strongly depending on the occupational rate and user age and activities. Mere measurements can very seldom give reliable data about the user comfort. The user feedback information should be collected as real-time as possible. The question about indoor comfort can be reliably answered only about current situation, not that from the day or week before. The applied novel system collected momentary feedback data, which is unique compared to typical questionnaires. Each given feedback could be connected to the indoor conditions measured at the same time. These principles were applied in this study aiming to find out the factors for comfortable indoor environment conditions in educational buildings. The presented study and results are based on a project reported on 2021 [3]. The results are mainly valid for the studied sites, but some findings may have wider relevance when evaluating the correlation between user experience and indoor environment.

2. Monitored sites

Four buildings, three educational buildings and one day care center, located in Helsinki and Espoo cities in the southern coast of Finland were monitored. All the buildings were renovated during the recent years and they had modern HVAC -systems.

Altogether 30 room spaces, mainly class rooms, were monitored and the user feedback was collected from these spaces. The indoor conditions of these selected room spaces were monitored using the data from the existing HVAC -automation system, additional measurement set-ups and space user surveys. The sensors of the additional measurements were placed close to the occupation zone of the room spaces, which gives supplementary information about the indoor conditions. Tab. 1 represents the monitored sites, the age groups of the pupils and the number of the monitored room spaces in each site. There was one feedback device in each of the monitored space.

Tab. 1 – Monitored buildings.

Building code	Purpose	Ages and number of pupils	Monitored room spaces
#1	Secondary and high school	12-18 (900)	6
#2	Day care center	0–5 (150)	4
#3	Primary school	6–13 (390)	10
#4	Vocational school	15–19 (900)	10

Typical classrooms (from 4 – 10 from each site) were selected for this analysis. The indoor environment feedback system was used by the personnel and the school children. More than 2000 persons were able to give feedback about the indoor environment of the spaces.

At least one year measurement and feedback data was collected from these sites during years 2019 - 2020. There were some interruption periods in the use of the school sites due to Covid-19 epidemic, but sufficient data could be collected for the analysis.

3. Indoor condition measurements

The indoor environment conditions were monitored in each space that had the user comfort feedback system. The condition data was collected from the HVAC automation system and using additional sensors placed in the occupation zones of the studied spaces. Typical data measured for the HVAC system were: Indoor temperature, CO2 -content, ventilation inlet and outlet air flow rates and temperatures. Additional measurements were carried out to ensure proper indoor data from the occupation zones of the room spaces. These measurements, collecting data every 10 minutes, included: Air temperature and humidity, CO2 -content, total content of volatile compounds (tVOC), particle contents of the air in three size categories (PM 1.0, PM2.5 and PM10). In some sites the pressure difference over the building envelope was monitored.

4. Feedback system

The feedback system tablet terminals were placed in the selected room spaces. They all had the same set of questions and answering categories. The feedback could be given for all or only for selected questions. Typically the feedbacks were given before and after the 45 or 90 minute class period, representing the perceived indoor environment when entering the space and during the working period.

4.1 Feedback evaluation classes

The feedback system asked about how the respondent finds out the current

- Temperature
- Humidity
- Freshness
- Odours
- Cleanliness
- Lighting
- Acoustics and voices
- Capability to work and learn.

The answering was based on defined representative choices. In the analysis, each choice was given a number. The following tables present some typical choices for the answers.

Tab. 2 present the choices for thermal comfort. Level 0 corresponds to comfortable conditions, higher values to warmer and negative to chilly or cold conditions.

Tab. 3 present the choices for air freshness. Level 0 corresponds to still tolerable conditions (not fresh/ stuffy), higher values to better and fresh conditions, negative to stuffy conditions.

Tab. 4 present the choices for the experienced capability to work and learn. Level 0 corresponds to still tolerable conditions (not good/bad), higher values to better, negative to worse conditions.

The same systematic way all the answering choices were formed.

It is obvious that the user experience of working and learning ability depends on several factors apart from indoor environment. The general atmosphere while working and teaching, the level of activities, how many pupils and teachers occupy the space, etc. have effect on the feedback. In this limited study these factors were not evaluated, and the feedback was compared with the measured indoor conditions.

Tab. 2 – Choices for the answers about thermal comfort.

Definition	Number
Hot	3
Warm	2
Slightly warm	1
Comfortable	0
Slightly chilly	-1
Chilly	-2
Cold	-3

Tab. 3 – Choices for the answers about air freshness.

Definition	Number
Fresh	2
Slightly fresh	1
Not fresh, not stuffy	0
Slightly stuffy	-1
Stuffy	-2

Tab. 4 – Choices for the answers about capability to work and learn.

Definition	Number
Good	2
Relatively good	1
Not good, not bad	0
Slightly bad	-1
Bad	-2

4.2 Real time feedback

Each feedback entry was attached to the exact entry time. This made it possible to link the given feedbacks with the monitored indoor environment conditions for the same time periods. The time interval for the measured data collection was typically 10 minutes. Each feedback could be connected to measured conditions during the last 10 minutes.

5. Analysis of the results

The measured and feedback data were combined to form correlations between different conditions and measurements. In the following only some of the clearest and most interesting findings are presented. Because the buildings were recently renovated, the HVAC systems performed quite well and, for example, the indoor temperature and CO2 -levels remained mainly close to the common comfort zone. Therefore, the perceived conditions very seldom had the utmost values and these correlations remained mostly quite weak.

The feedback level of each indoor environment factor was given a number corresponding to the level of comfort (Tables 2 - 4). The distributions of the feedback classes were formed and for each level of comfort the concurrent measured average values of different indoor environment factors could be solved. The correlations were formed using this data. For example, when the indoor conditions were experienced hot (perceived indoor temperature level = 3), the average of all the measured concurrent conditions could be solved. Each experienced condition level corresponds to certain concurrent average measured factors.

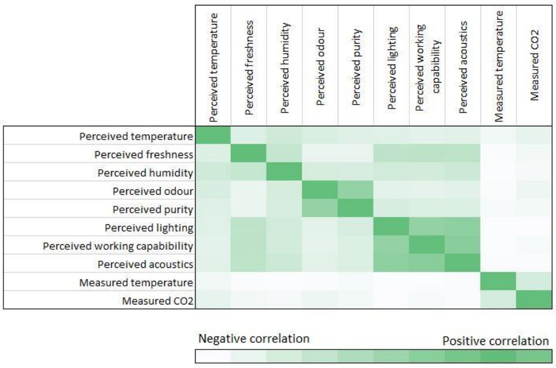
The presented results are preliminary. Proper statistic approach was not yet applied, partly due to the strong variation on the number of feedbacks for different factors.

5.1 Correlations between perceived conditions

Correlations between the different feedback conditions reveal how the different factors affect each other. In schools and offices one of the most important factor is the user experience about how well and effectively one can work and learn in such conditions. This feedback question gives the best overall number for the indoor environment quality.

The cross tabulation of the feedback results shows clear correlations between the *capability to work and learn* with the perceived *lighting* and *acoustics* conditions, and also some correlation with the *freshness* of the air. Tab. 5 present the correlations between the different factors of indoor environment derived from the feedback data.

Tab. 5 – Correlations between the different experienced conditions.



The recently renovated HVAC systems maintained relatively stabile and comfortable conditions throughout the monitored periods, which reduced the possibility to define the effect of wide range of conditions, for example with temperature and CO2 -contents clearly close or out of comfort boundaries.

5.2 Correlations between feedback and measurements

The age categories of the building users varied from building to building and, also the activities in the buildings differed from each other. The main results from each building are presented separately.

Two measured values represent two measurement sites from the living space of each room. Typically one close to occupation zone and one close to air outlet device. This gives an idea of the distribution of the inside conditions.

School #1

The feedback for school #1 during the year 2019 was compared to the measured values and the main findings are presented in the following figures. Measurements are typically from two sites from the living space of each room to show the distribution of the inside conditions.

Fig. 1 present the dependency of the temperature and relative humidity levels on the experienced indoor temperature and Fig 2 presents the correlation between thermal comfort and indoor air enthalpy. Low increase in the average relative humidity and enthalpy level increased the feedback proportion in classes too warm or hot.

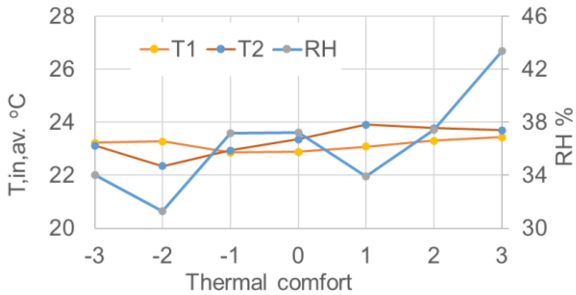


Fig. 1 – Dependency of the temperatures and relative humidity levels on the thermal comfort conditions in all the monitored spaces of the school #1 during 2019.

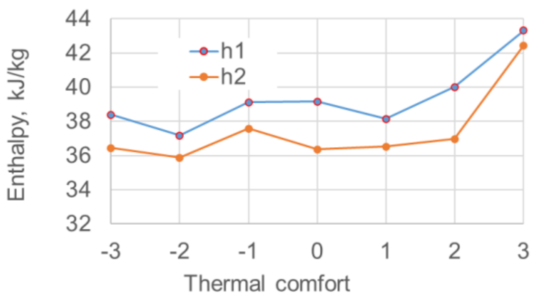


Fig. 2 – Dependency between the indoor air enthalpy and the thermal comfort conditions in all the monitored spaces of the school #1 during 2019.

Increased enthalpy level affected the experienced freshness of the indoor air (Fig. 3)). This is in line with the publications [4 and 5]. Also, higher CO2 -levels contributed to feeling of the stuffy air (Fig. 4). This correlation is most probably indirectly under these CO2-contents and it is related to other loads in the air.

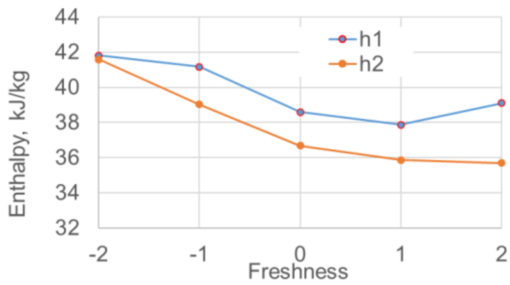


Fig. 3 – Dependency between the indoor air enthalpy and the user perceived freshness of indoor air of all the monitored spaces of the school #1 during 2019.

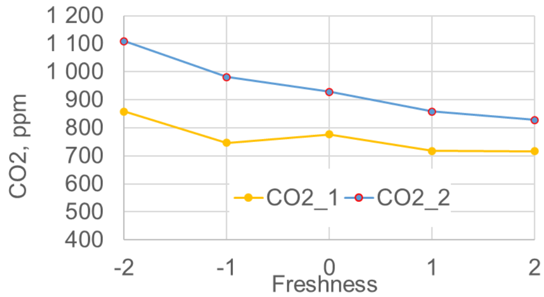


Fig. 4 – Dependency between the indoor air CO2 - content and the perceived freshness of indoor air of all the monitored spaces of the school #1 during 2019.

The correlations between *the ability to work and learn* with the measured factors of indoor air were not very clear. About 97 % of the feedbacks for the capability to work and learn (n=201) were in the level 'reasonable' or better (numbers 0 – 2). Due to marginal number of negative experiences, no good correlations could be found for this factor. Fig. 5 shows how the distribution of three factors - *the capability to work and learn, lighting and acoustics* – are almost identical.

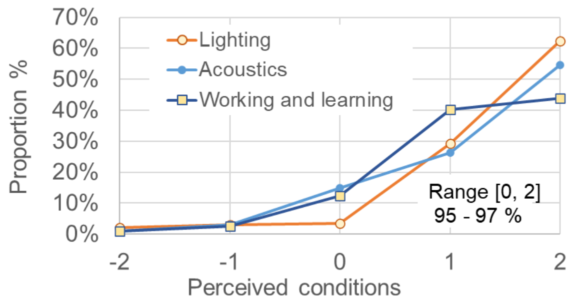


Fig. 5 – Distribution of the perceived conditions of lighting, acoustics and capability to work and learn in all the monitored spaces of the school #1 during 2019.

Day care center #2

The feedback was collected only from the personnel of the day care center. The feedback for the year 2020 was compared to the measured indoor environment values and the main findings are presented in the following figures.

The perceived thermal comfort was relatively sensitive to the indoor air enthalpy level (Fig. 6). The variation of enthalpy was mainly caused by the relative humidity.

The experienced capability to work depended on the indoor air CO2 -levels (Fig. 7). This most probably linked to other factors than only CO2-level that was on an average quite low. While the CO2-level refers to the occupation rate of the room space, some other factors may have affected the working capability when the room was more crowded. This is partly supported by the dependence on total VOC -content. The lowest experienced capability to work was found with the highest tVOC -levels (Fig. 8).

The experienced air freshness was clearly reduced with higher air enthalpy and CO2 -levels (Figs. 9 and 10)

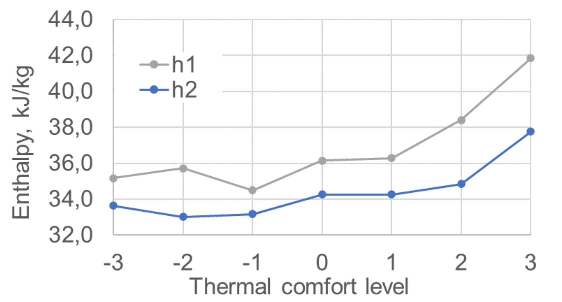


Fig. 6 – Dependency between the indoor air enthalpy and the thermal comfort conditions in all the monitored spaces.

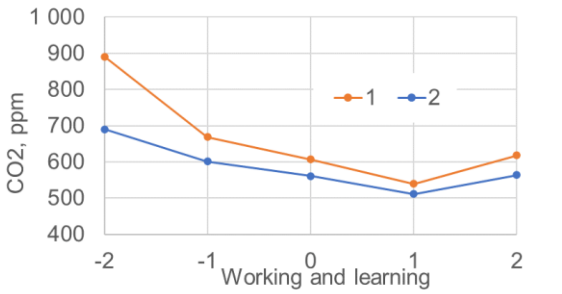


Fig. 7 – Dependency between the CO2 -content and the capability to work and learn in all the monitored spaces.

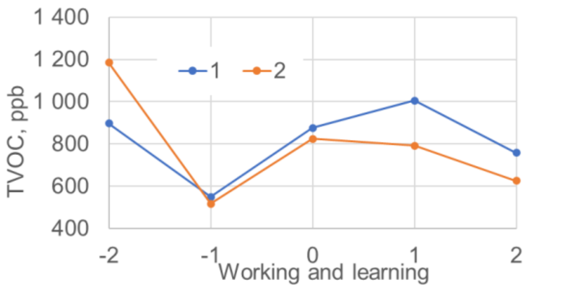


Fig. 8 – Dependency between the total VOC -content and the capability to work and learn in all the monitored spaces.

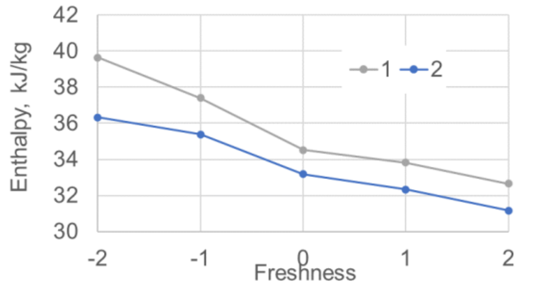


Fig. 9 – Dependency between the enthalpy level and the perceived freshness of indoor air.

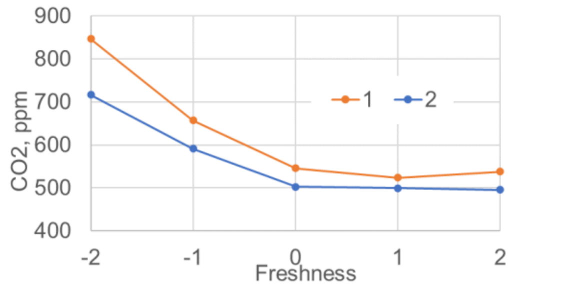


Fig. 10 – Dependency between the CO2 - level and the perceived freshness of indoor air.

Primary school #3

The following represents the comparison between the feedback and measured factors in a Primary school #3 during the year 2019 and partly during 2020. The feedback was collected both from the pupils and school personnel.

This school was a good example about well performing, adaptive HVAC -system. The feedback referred to relatively good conditions and it was distributed so that no clear correlations with indoor air conditions could be found. As examples, the dependency between thermal comfort (n = 4142) and indoor thermal measurements (T, RH, enthalpy) are presented in Fig. 11 and that between the experienced freshness (n=1993) and CO2-level in Fig. 12. In both figures the measured conditions varied in a very low range and apparently corresponded relatively well to comfortable indoor conditions.

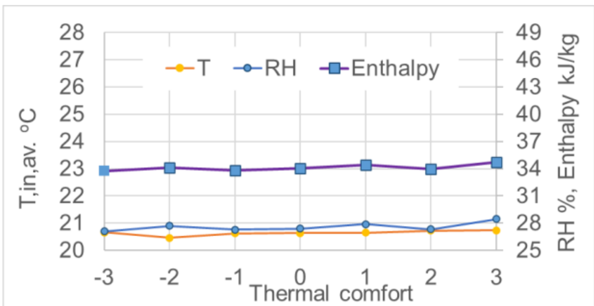


Fig. 11 – Dependency between the indoor air temperature, humidity and enthalpy levels with the thermal comfort conditions in the monitored spaces.

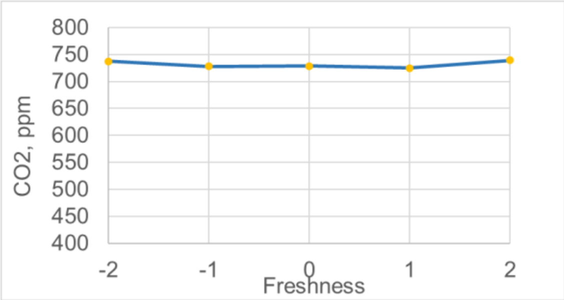


Fig. 12 – Dependency between the CO2 - level and the perceived freshness of indoor air.

Vocational school # 4

In the vocational school the results mostly corresponded to that with the Primary school #3, no clear correlations could be shown between the feedback and measured values. This was partly due to the relatively stabile indoor conditions.

Some interesting findings can be presented. The experienced capability to work and learn (82 % from feedbacks , n=147, found it satisfying or better) that has a positive dependence of total VOC content. This was quite the opposite that was expected or what was found in the day care center. Fig 13 presents the average results for all the monitored spaces and one space 144 meant for hair dressing practices. It seems that some VOCs were positively linked to learning and practicing in this school.

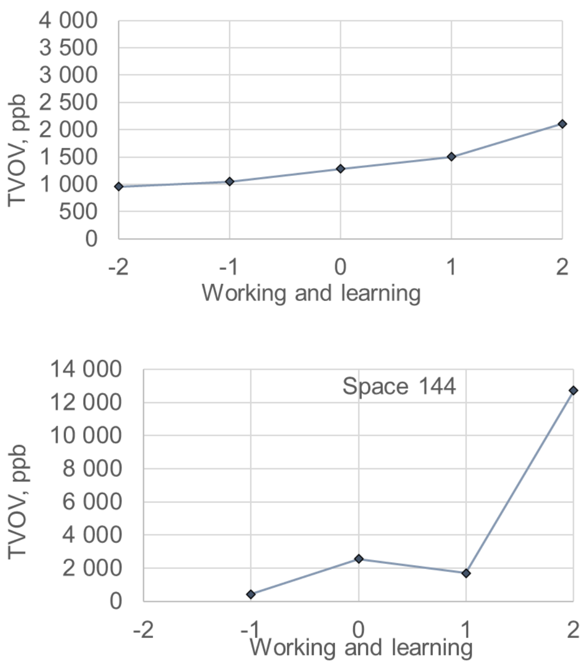


Fig. 13 – Unexpected dependence of working and learning capability with the total volatile compound contents. Above the average for all the monitored spaces and below the for the space for hair dressing practices.

The experienced working and learning capability had some negative correlation with the direct solar radiation measured in the in the weather station close to the site (Fig. 14). The building has large window areas facing south. The effect of solar radiation could not be clearly seen in thermal conditions, but maybe the solar radiation caused possible glare that affected the experienced working conditions.

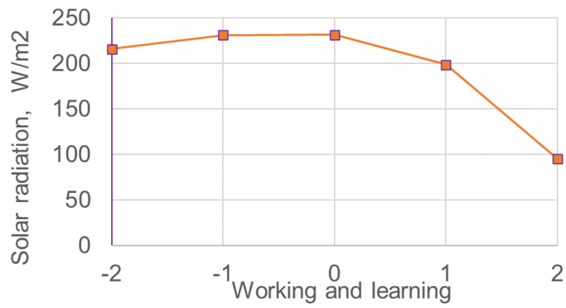


Fig. 14 – Dependence of working and learning capability with the direct solar radiation measured in the weather station close to the site.

5.2 Normal vs. full time ventilation

In all the sites during the occupation hours ventilation is controlled based on the CO2 -levels of the spaces. For energy saving purposes the ventilation is closed outside the occupation times and it is started two hours before the daily working begins.

By mistake, the ventilation in the Primary school #3 was used full time without interruptions (24/7) for a 16 days period (27.8.–12.9.2019). The users didn't know about this. This occurrence made it possible to compare how the different ventilation modes affected the user experience of the indoor climate.

The following results present the comparison of the feedback results between the full time (24/7) and typical intermittent ventilation schemes. The normal, intermittent ventilation periods were taken from both sides of the 24/7 ventilation period (6.–26.8. and 13.–30.9.2019).

The following figures (Figs. 15 – 19) present the comparison between indoor air user experience from the normal and 24/7 periods. The comparison is presented as a sum of the perceived level of satisfaction starting from the best experienced conditions on the left of the x-axis. The proportion level represent which portion of the feedbacks correspond to the experienced level on x-axis or are better than that.

For example, the perceived temperature (Fig. 15) was best possible (neutral, value 0) in case with normal ventilation scheme in about 30 % of the total number of feedbacks during to selected period. The conditions were acceptable (between -1, 1) in about 47 % of the feedbacks, meaning that about 53 % considered the indoor conditions to be too warm or cold. The distribution of all the other experienced conditions are presented in the same way in Figs. 16 – 19.

The difference between the experienced temperature condition in 24/7 and normal ventilation cases was very low.

The only difference between the cases was detected in the feedback levels of the cleanliness of the air (Fig. 17), where the normal ventilation scheme showed better (higher values in lower values indicating better cleanliness) user comfort than the 24/7 scheme. This difference remained inexplicable, but could be partly due to the low number of feedbacks for this question. The 11-step scale used in the cleanliness and odour feedbacks was not clear enough and caused some focus on the maximum value.

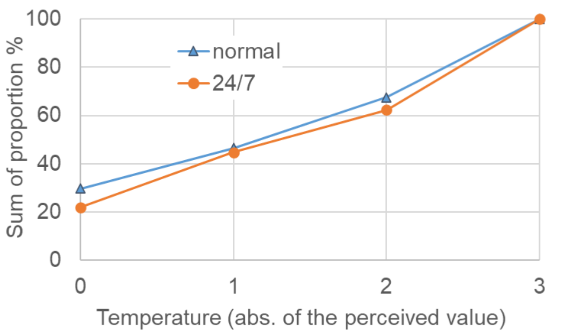


Fig. 15 - Distribution of the temperature feedbacks presented as a sum starting from the best conditions.

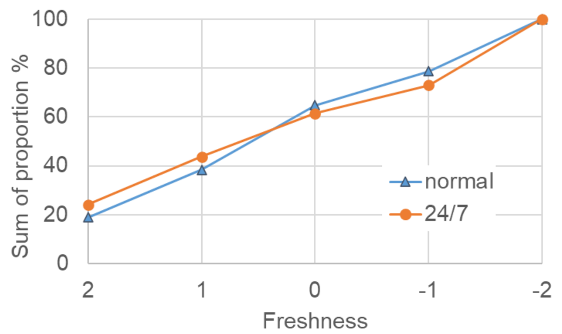


Fig. 16 - Distribution of the air freshness feedbacks presented as a sum starting from the best conditions.

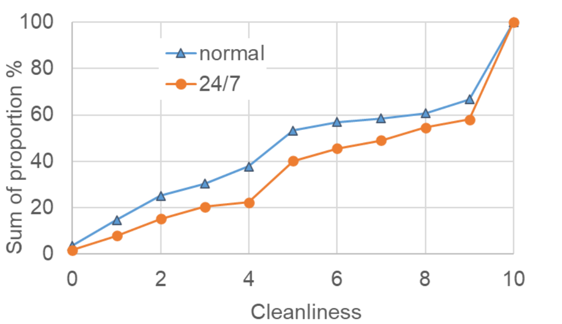


Fig. 17 - Distribution of the air cleanliness feedbacks presented as a sum starting from the best conditions.

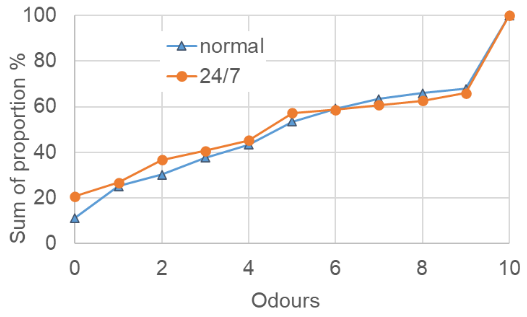


Fig. 18 - Distribution of the feedbacks about odours presented as a sum starting from the best conditions.

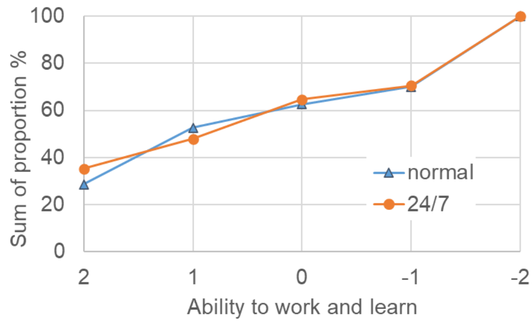


Fig. 19 - Distribution of the feedbacks about capability to work and learn presented as a sum starting from the best conditions.

6. Discussion and conclusion

The capability to work and learn is one of the main goals of user experience. This is emphasised in educational buildings, and the same criteria is applicable also in offices, homes and other buildings.

In this study three educational buildings representing different grades and one day care center were studied at least for a one-year period to find the main factors affecting the perceived indoor environment comfort. In total, the indoor conditions of 30 selected room spaces were monitored and the perceived comfort of the users was collected through a novel real-time feedback system. Each feedback could be connected to the right indoor conditions measured at the same space and at the same time range.

The selected buildings had been recently renovated HVAC -systems with adapting ventilation systems. Therefore, the utmost conditions of at least air temperature and CO2 -content, were missing and the analysis is based mainly on the conditions close to typically known comfort zones.

The results are mainly valid for the studied sites, but some findings may have wider relevance when evaluating the correlation between user experience and indoor environment.

The experienced feedback results showed clear correlations between the capability to work and learn with the perceived lighting and acoustics conditions, and some correlation with the freshness of the air.

While the indoor temperature levels remained mostly in reasonable levels in the studied buildings, the thermal comfort depended mainly on the relative humidity levels. The correlation between thermal comfort and indoor air enthalpy (energy level combining temperature and relative humidity) level was even more clear. Typically, the thermal comfort was reasonable until some level of enthalpy, and with higher values the feeling of too warm condition increased clearly. This turning point value depended on the use of the building and the age and activity of the users. Compared to the comfort zones presented in ASHRAE [5 and 7] the comfort conditions in these buildings remained in the lower side of temperature and humidity. High indoor air enthalpy levels also affected the perceived air freshness.

The total VOC -levels didn't have much effect on the perceived air freshness. Even unexpected positive correlation between the capability to work and learn and the tVOC-levels were found, which partly reveals the uncertainty with respect to the interpretation of the total VOC -measurement results.

One important finding was that there were no difference in the experienced indoor conditions when comparing a case with full time ventilation with a typical case where the ventilation was shut down outside the working hours. This finding supports the energy efficient use of the ventilation system.

The applied methodology where the real-time feedback results are combined with the concurrent measured indoor data seems to be reliable when evaluating the factors having effect on the experienced indoor environment. Further studies with buildings having older technical systems, different user activities and separating the seasonal effects are needed to broaden the perspective for the factors of good indoor environment.

7. Acknowledgement

This work is based on the results from Indoor Air 2020 -project (Sisäilma-2020, 2019 -2020) that was funded by the Cities of Helsinki, Espoo and Vantaa and by VTT Technical Research Centre of Finland Ltd.

8. References

[1] RT 07-11299, Classification of Indoor environment 2018. Indoor environment target values, design guidelines and requirements for products (in Finnish). 24 p.

[2] Likert scale. https://en.wikipedia.org/wiki/Likert_scale

[3] Ojanen, T., Vesanen, T., Kannari, L., Piira, K., Nykänen, E., Tuomainen, M., Naumi, H., Lumme, T., Melender, M., Vene, E., Markkanen, P., Åberg, J. & Mattila, J., Indoor climate 2020: Factors for good indoor environment in schools and daycare centers (in Finnish) 2021, VTT Technical Research Centre of Finland. 137 p. (VTT Technology; No. 388).

[4] Fang, L., Clausen, G. and Fanger P.O. Impact of temperature and humidity on the perception of indoor air quality. *Indoor air 8*. 1998. pp. 80 – 90.

[5] Fang, L., Clausen, G. and Fanger P.O. Impact of temperature and humidity on chemical and sensory emissions from building materials. *Indoor air 9*. 1999. pp. 193 – 201.

[6] ANSI/ASHRAE Standard 55-2010. Thermal Environmental Conditions for Human Occupancy.

[7] Tartarini, F., Schiavon, S., Cheung, T., Hoyt, T., 2020. CBE Thermal Comfort Tool : online tool for thermal comfort calculations and visualizations. SoftwareX12,100563. https://doi.org/10.1016/j.softx.2020.100563