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The creation of SenseLab: a laboratory for testing and experiencing single and combinations of indoor environmental conditions

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ABSTRACT
Research has shown that staying indoors is not good for our health. People spend more and more of their time indoors. Therefore, providing a healthy and comfortable indoor environment is very important. The SenseLab will contribute to the understanding of and coping with the indoor environment. Students, teachers, researchers, but also the general public are able to experience and test different combinations of environmental conditions. The SenseLab is built around the four indoor environmental quality (IEQ) factors (air, thermal, light and acoustical quality), including: the experience room, for integrated perception of IEQ, so studying all factors together. And four test chambers, open to the public, where you can take a sniff of materials, feel heat and cold, see how light influences perception and experience how acoustics can be improved. A genuine playground for your senses.

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Introduction

How to achieve a healthy and perceptually fluent indoor environment has been an issue among architects, engineers and scientists for centuries. Previous research has shown that for the establishment of basic requirements and needs a different view on indoor environmental quality (IEQ) is required, in which the focus is on situations rather than single components. Also, a multidisciplinary interactive top-down approach is required to facilitate the design, construction, maintenance and operation of an indoor environment, in which the architect as well as the other stakeholders fulfil a new or different role. This new role requires a multidisciplinary education and research programme that can help to fulfil the need for multidisciplinary people in the building industry (Bluyssen 2013).

To facilitate this multidisciplinary education and research programme, the 'SenseLab', a playground for the senses, has been built at the Science Centre (part of the premises of the Delft University of Technology), in which single and combinations of environmental conditions can be both experienced and tested.

The research performed in the SenseLab will contribute to the development of a new assessment approach, which takes account of the combined effects of stress factors in buildings on people (patterns) as well as their individual profiles, and can be used to determine requirements (to prevent

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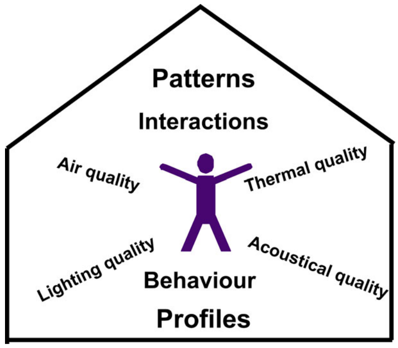


Figure 1. Conceptual approach.

negative effects) and preferences (to stimulate positive experiences) for (re)designing healthy and comfortable buildings (Figure 1).

SenseLab

General outline

The SenseLab is built around the four IEQ factors (air, thermal, lighting and acoustical quality) in a room of the Science Centre in Delft, The Netherlands (Figure 2) and comprises (see Figure 3):

- *The experience room*, a room of circa 6.5 × 4.2 m^2 gross for integrated perception of IEQ in a semi-lab environment (Figure 4(a)).
- Four *test chambers* for each of the four factors, two circa 2.4 × 3.9 m^2 gross and two circa 2.4 × 2.6 m^2 gross. In principle, the four rooms are designed with similar basic features and a number of flexible features (Figure 4(b,c)).
- Two air handling units (AHUs) in the basement, one for the experience room and one for the test chambers.

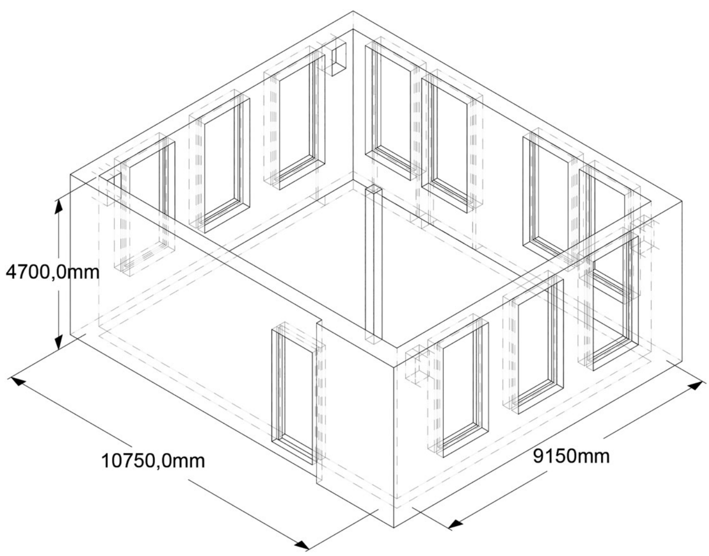


Figure 2. Isometric overview of the available space and its dimensions (in the Science Centre in Delft, The Netherlands).

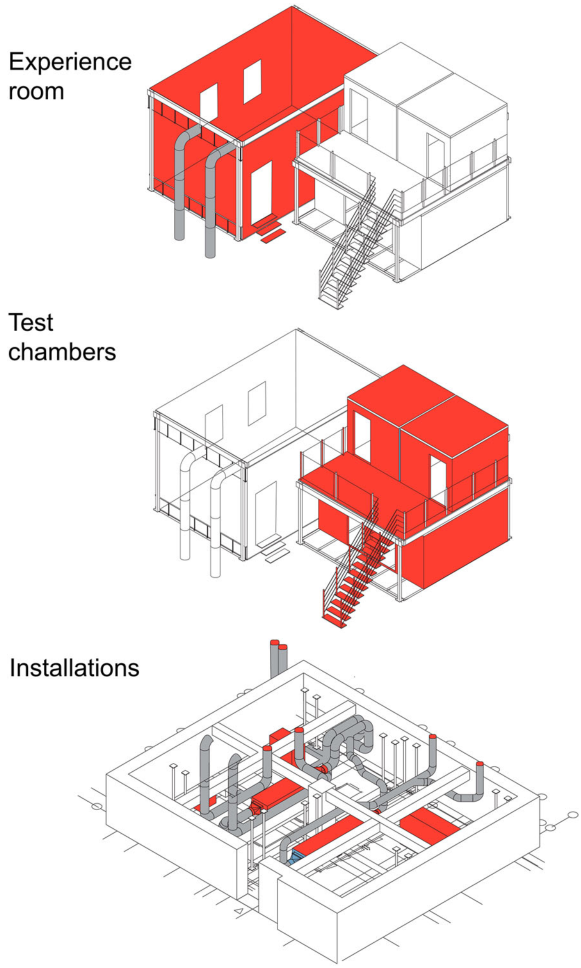


Figure 3. The SenseLab parts: experience room, test chambers and installations in the basement.

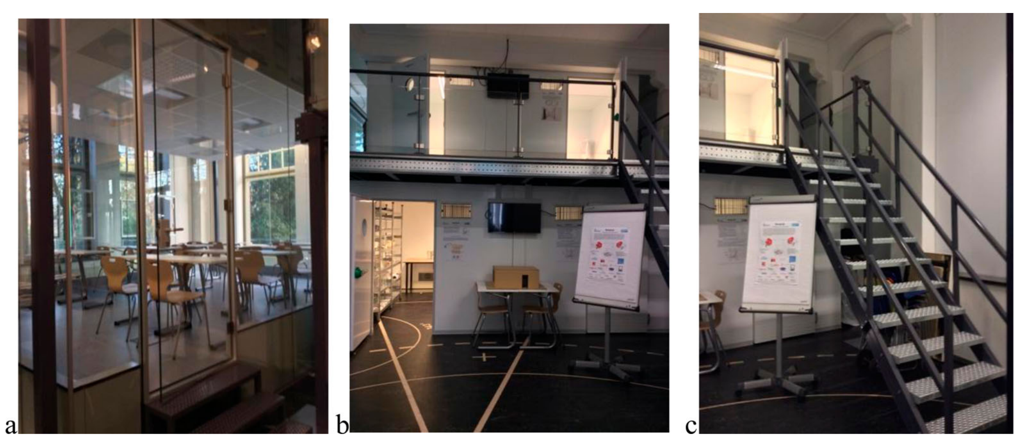


Figure 4. (a) Experience room, (b) test chambers and (c) stairs to first level of test chamber construction.

Design requirements

Additional to the design requirements of the experience room and the test chambers (see further on), the following design requirements were set for the SenseLab:

- Use of low-emitting materials to ensure a good air quality.
- The possibility of several operable windows, to have the option to ventilate naturally in the experience room. These windows should be integrated in the existing windows – as a 'window-in-window' construction (see Figure 7(c)).
- Additional electrical capacity to ensure a safe and sound operation of all the installations applied.
- Control systems for light, sound, ventilation, heating and cooling, for both the experience room and the test chambers.
- Tapping point for water, preferable nearby the entrance on the wall and therefore an additional hole in the floor for the water pipes (domestic water supply and waste water piping) is required.
- Because the two AHUs that need to be placed in the basement, the ductwork from the HVAC (heating, ventilation and air conditioning) systems require several holes in the floor (see Figure 5(a,b)) (structural analysis is not reported here, but the drilling of the holes in the floor resulted in the need for a temporary and local strengthening of the floor by skores).
- To prevent condensation of cooled air in the summer, the supply ducts should be externally insulated (thickness: 20 mm) (see Figure 5(c,d)).
- Ductwork should provide a stable and low noise level, preferable round ducts with a diameter large enough to make certain that the airflow is lower than 3 m/s (see Table 1) (NEN 2015).
- Short circuiting of the inlet and outlet of the AHU on the outside needs to be prevented. A study was made to investigate the different options based on the calculation method for the dilution factor described in NEN 1087 (NEN 2001) and the requirements given in the Dutch Building decree (Overheid.nl 2012) (see Figures 6 and 7).

HVAC systems

For the HVAC systems, the following design requirements were defined:

- The fans should be speed controlled.
- The outside air conditions summer: 28°C/60% RH (relative humidity); outside air conditions winter: −10°C.
- The AHUs should be as clean as possible (inert if possible), easy cleanable and have inspection doors.

Figure 5. (a) Drilling of the holes for (b) the ductwork and Insulation of the ducts in (c) in the basement and (d) before entering the experience room.

Table 1. Diameter selection of the ductwork applied (based on diameter^2 $\pi/4$ and max. 1000 m^3/h).

Duct	Hole diameter (mm)	Duct diameter (mm)	Volume (m^3/h)	Velocity (m/s)
Supply experience room floor (with insulation)	435	355	1000	2.8
Supply experience room ceiling (with insulation)	435	355	1000	2.8
Return experience room floor	400	355	1000	2.8
Return experience room ceiling	400	355	1000	2.8
Supply test rooms 1	325	250	400	2.3
Supply test rooms 2	325	250	400	2.3

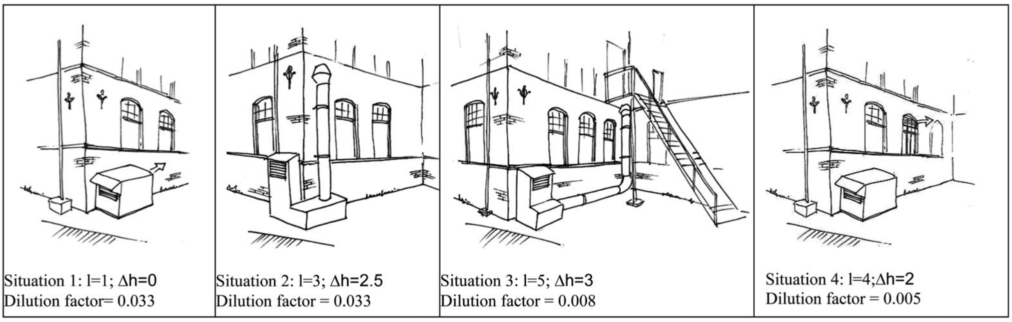


Figure 6. Sketch of the different options for locations of the new inlet and outlet (l = horizontal distance between the opening of the inlet and the outlet in m; Δ*h* = length of line between the inlet and the outlet in m). Even though option 4 resulted in the best dilution factor, it requires an additional hole in the floor, and was therefore not selected. Option 1 and 2a are not fulfilling the criteria of dilution factor <0.01 as given in the Dutch Building Decree (Overheid.nl 2012). Therefore, option 3 was selected (see Figure 7).

- The required sound level of the connections of the AHU to the building should be low, even without the use of silencers in the AHU.
- The cooling unit should be located outdoors (see Figure 7(b)).

Control systems

The control systems for HVAC and lighting are physically located in the basement. Next to the experience room, computers make it possible to manage those systems, including the audio system.

All light armatures are controlled via an advanced lighting controller (Excellium II from ETAP) based on Digital Addressable Lighting Interface, an International Standard (IEC 62386) for the control of electronic ballasts, transformers, LEDs, emergency lights and exit signs. This controller makes

Figure 7. Current situation of the inlet and outlet (a), the cooling system (b) and the ‘window-in-window’ construction (c).

it possible to change the luminance level per armature and to change the patterns of lighting (different scenarios).

The HVAC system controller (Priva Bleu controller) is managed by the programme 'TC Manager' (from Priva). Together with the programme 'TC history' and the sensors placed in the ducts and different rooms (experience room and test chambers), it is possible to control air temperature and ventilation rate. For the experience room, it is also possible to select the ventilation principle: mixing or displacement.

The sound system for the experience room is controlled by digital signal processing software on the computer. This software enables individual audio output from each of the speakers and subwoofer, as well as mixing of the signals.

The experience room

Purpose

In the experience room, it should be possible to study the effects, positive and negative, of different combinations of environmental conditions (thermal, sound, lighting and air) in different scenarios (office workers in office buildings, children in schools, people in their homes saving energy, etc.), by changing the interior design and choice of materials and systems:

- Change the light (distribution) by changing materials (instead of lighting), but also by changing the light itself.
- Changing the sound (distribution) by changing materials or make use of movable panels, or by introducing noise (sounds) on purpose (by a sound system) or not (e.g. noise from ventilation systems).
- The effect of different heating and air conditioning means on personal climatization and well-being.
- Choice of design, materials and systems in relation to air quality.
- Assessment of total experience and well-being (health and comfort)!

Design requirements

For this to be possible, the following design requirements were defined:

- The internal materials should be changeable: the floor, ceiling, but also the walls should be possible to be changed.
- The basic construction material should comprise low-emitting materials.
- The lighting system should comprise different types and amount of lighting armatures (diffuse, direct and indirect light) and should be possible to dim and control individually.
- A sound system that can produce noise/sound within a range from 0 to 100 dB, and from 25 Hz to 20 kHz, is required.
- Different types of ventilation are required: mixing, displacement and natural ventilation. Thus, fully air conditioning but also natural ventilation and mixed-mode regimes.
- Air supply and air exhaust are *not* interchangeable in order to keep the supply ductwork clean. This required separate supply and exhaust ducts, in both floor and ceiling plenums.
- The AHU should be able to provide a variable airflow with a range of 0–1000 m^3/h or air exchange range from 0 to 10/h based on 10 persons with 25 l/s person (see also general requirements).
- Heating and cooling possibilities of air with a range from 15 to 25°C.

Features

The experience room comprises several components:

- A coated steel frame (low-emitting) for maintaining the structural integrity of the experience room.
- Walls of 2 × 8 mm laminated glass (inert material) to be sure of sufficient structural strength and make it resistant to incidental impact with the possibility to add different panels of materials from the inside.
- Two plenums (below and above), through which ventilation, heating/cooling, lighting and acoustics can be provided/changed.
- The floor is flexible (raised computer floor) and built in the room on the floor of the SenseLab. The ceiling of the room comprises a panel construction. Basic components selected comprise low-emitting and/or inert materials.
- Stair to enter the experience room and a door.
- Operable windows are integrated in the glass structure (with a possibility to be connected to the operable outdoor windows of the SenseLab) (Figure 8).

Air quality and thermal comfort

There are different air supply and air exhaust possibilities (Figures 9 and 10):

- Displacement ventilation from floor to ceiling by using a perforated plinth (just above the floor on the long sides of the experience room) and exhaust in the ceiling on the side; and
- Mixing ventilation from ceiling to floor: air supply in plenum (via four ceiling grilles 600 × 600 mm from TROX) and exhaust in perforated plinth on the short side of the experience room.

Based on an analysis of the perforation rate, maximum velocity in a hole (perforation) of 0.3 m/s and existing displacement grids, the holes of the air supply in the plinth were selected to be 3 mm, with a plinth height of 160 mm and a perforation rate of 20–33% in order to minimize noise. The holes of the exhaust plinth are chosen to be identical because of aesthetics.

Figure 9 shows a schematic overview of the installations under the floor, Figure 10 the ductwork, Figure 11 the plinth and Figure 12 shows the supply (mixing) and exhaust (displacement) via the ceiling.

Acoustical and light quality

Both acoustical and light quality can be changed by changing the materials of the walls, ceiling and floor inside the experience room and changing the furniture inside the room. In the ceiling

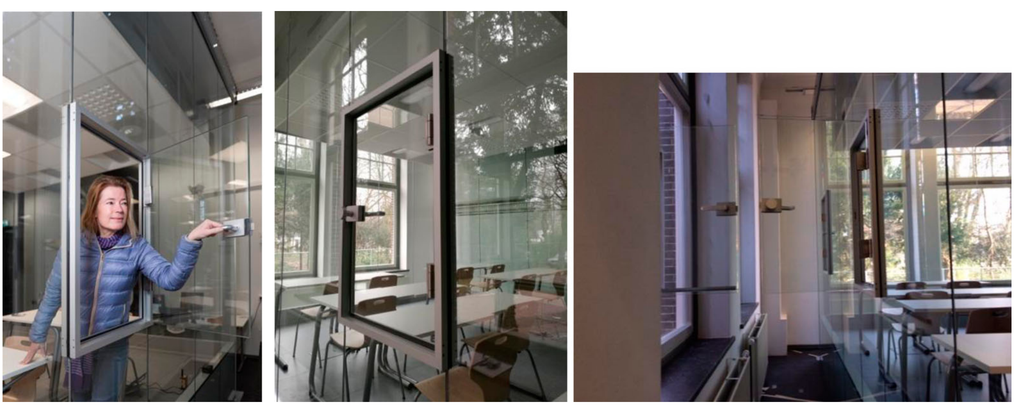


Figure 8. Operable windows in the experience room and the SenseLab.

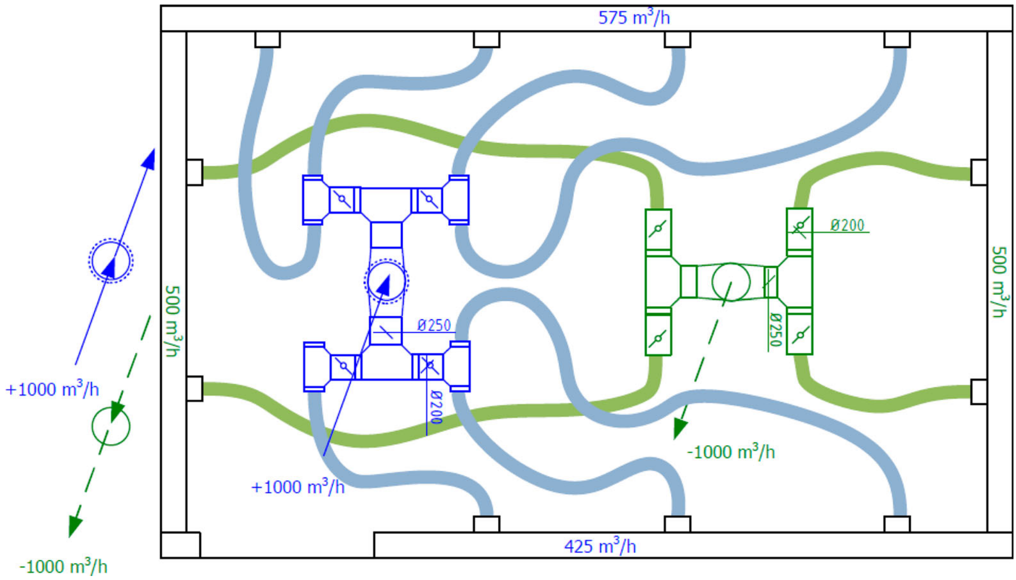


Figure 9. Schematic overview of the ducts and the airflows under the floor of the experience room.

and floor, the panels can be exchanged, while on the inside of the glass walls, panels can be added.

Besides the four air supply grilles, the ceiling of the experience room includes:

- Four independently controlled ceiling mounted loudspeakers (near-/midfield studio monitors, three-way, 2 × 7″ woofer, ADAM Audio A77x) and a subwoofer (200W, 1 × 10″ MKII, ADAM Audio Sub10) (from AMPTEC) above the suspended ceiling, connected to a 32-channel (16 in/16 out) audio interface (Behringer FCA 1616 Firepower) connected to a computer with sound editing software, with which it is possible to create different types of sound/noise.

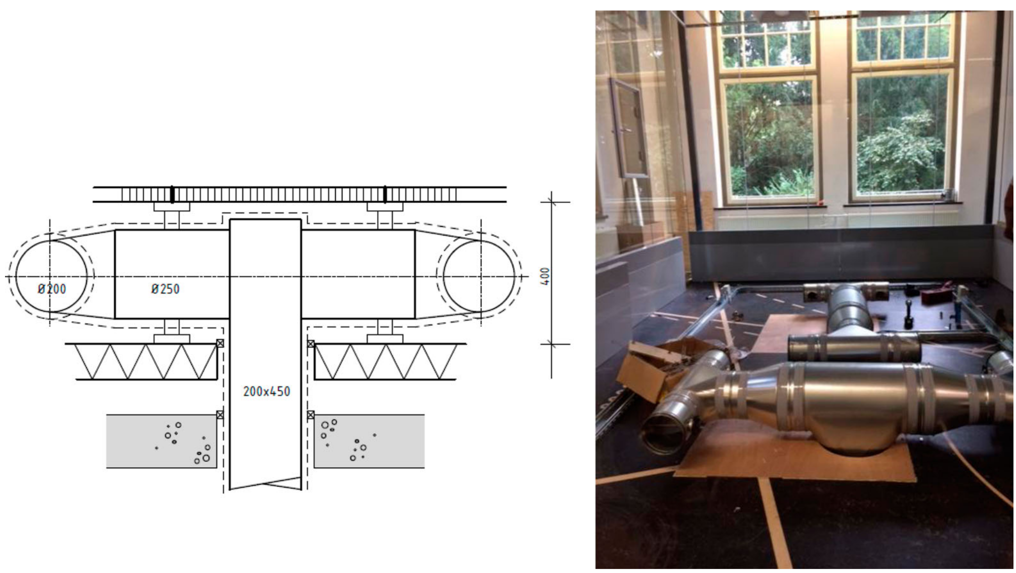


Figure 10. The ductwork under the floor of the experience room: (a) schematic (b) during construction.

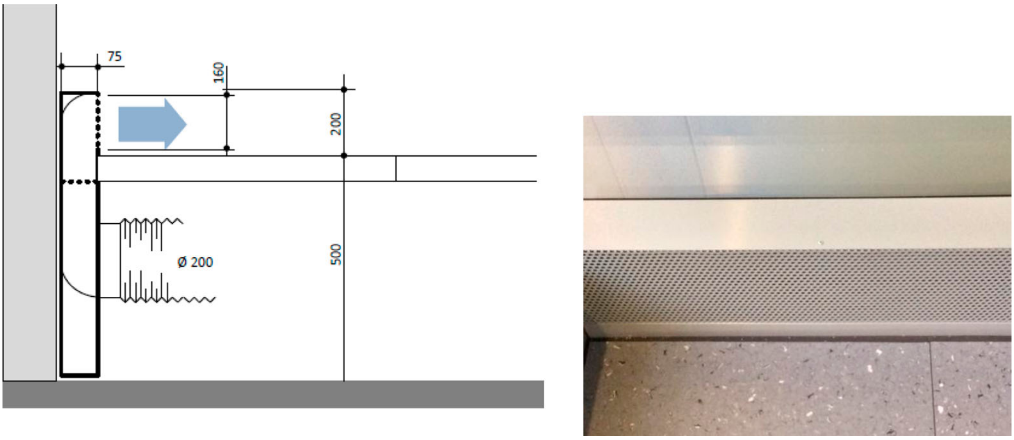


Figure 11. The plinth with supply air on the long sides of the experience room: (a) schematic (b) current.

- Three types of lighting armatures: four direct light led (HP 55 W), four indirect light led (LP 40 W) and eight soft light led (LP 28 W) armatures (from ETAP), which can be controlled from a PC, laptop and/or tablet, and gives the possibility to change the distribution, intensity and diffuseness of light.

Figure 13 shows a schematic overview of how the lighting system, the HVAC system and the acoustical systems are divided over the ceiling.

Test chambers

Purpose

In each of the four test chambers, several features are present with which the environmental parameter in question can be illustrated and tested. These exhibits will be flexible. Some goals of these specific test chambers and first features are presented below.

Air quality

- To visualize and perceive how a portable HVAC system (with removable parts) operates.
- To smell and evaluate different furnishing materials under different conditions (wet, dry, mixed) with smelling devices (see Figure 14(a)).
- To demonstrate and apply human performance testing equipment (e.g. spirometer peripheral arterial tonometry + software).

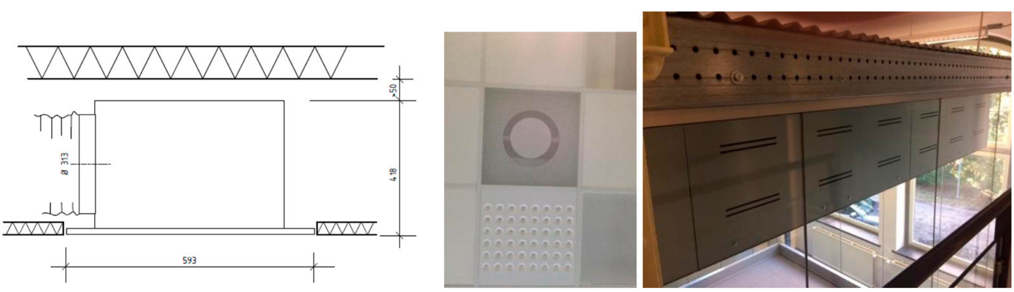


Figure 12. The ceiling of the experience room: (a + b) supply (mixing) and (c) exhaust displacement via ceiling.

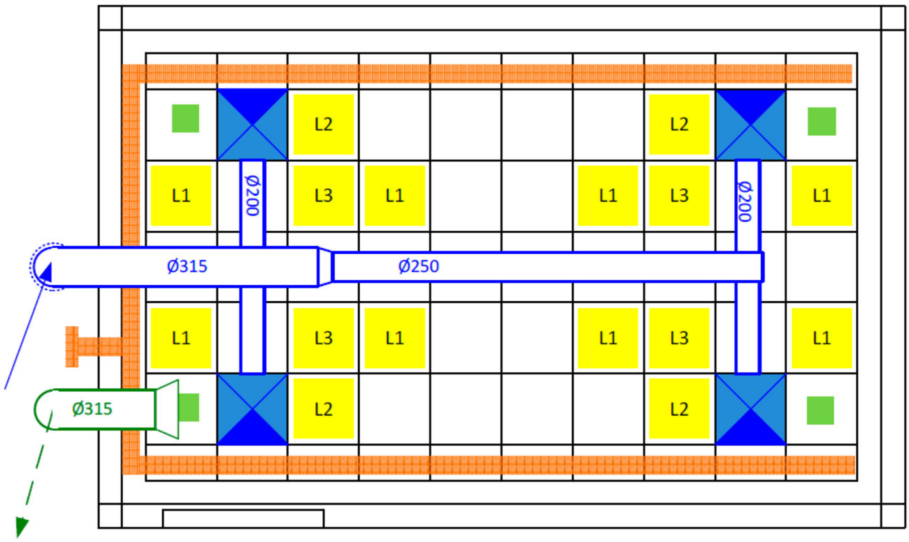
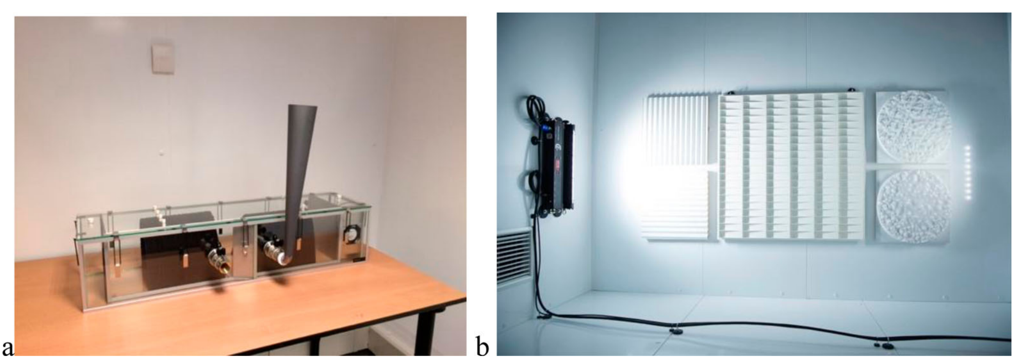


Figure 13. Schematic view of how the lighting system, the HVAC system and the acoustical systems are currently divided over the ceiling of the experience room (yellow: lighting system (L1 is soft light, L2 is direct light and L3 is indirect light; blue: air supply; green: loudspeakers).

- To demonstrate and apply environmental monitoring devices (NO_x, Ozone, CO_2/CO, (T)VOC).
- To experience different ventilation rates and learn about source control.

Thermal quality

- To demonstrate, experience and learn about alternative heating and cooling system(s), such as radiant heating (versus convective heating), local electrical heaters, humidifiers and cooling devices.
- To learn, experience and measure different temperatures (radiant, air), draught and humidities with temperature and humidity sensor equipment, questionnaires and performance tests.
- To learn about how heat exchange between humans and their environment works in other scenarios than sitting behind a desk (e.g. cycling and running machines) and human physical testing (e.g. ECG, finger probe).



a b

Figure 14. Current exhibits for air and lighting: (a) to smell different pollution sources and learn about them (b) to perceive how shape, material and space appearance can be influenced by the lighting of it.

Lighting quality

- To demonstrate effects of light, and the distribution of light by interior design and choice of materials (see Figure 14(b)).
- To learn, experience and test responses of people (e.g. visibility and comfort of specific qualities of the environment) to different situations (e.g. low versus high contrast or diffuseness and homogeneity) in order to optimize the resulting light distribution in the space depending on task and context – in terms of functional, perceptual and atmosphere attributes.

Acoustical quality

- To demonstrate, experience and learn about the perception of different acoustical sources (e.g. speech, phone conversations, air conditioning systems, traffic from outside, sound levels and annoyance) and low frequent vs. high frequent sounds.
- To learn, experience and measure the perception of different acoustical situations by changing materials, changing the sound and using subjective perception as well as human physical testing (e.g. heart rate meter, blood pressure).

Design requirements

The inside of each test chamber needs to have a similar floor plan, so the chambers are flexible in use and interchangeable:

- On one side, an exhibition is present and on the other the possibility to do some tests for the public.
- On the back side, a real test set-up is created, which can be used as well for experiments.
- An AHU is required to supply air to the four test chambers. A constant airflow rate is required (with a speed control), as well as a relatively low noise level.

Features

The four test rooms are designed with similar basic features:

- Basic construction constructed of smart protect white antimic low-emitting wall panels (without floor);
- Cold room revolving doors with the addition of a round window; and
- Holes at the back of the test rooms for air supply (425 × 225 mm) and holes (425 × 225 mm) in front for exhaust (based on overflow) (see Figure 15).

While the air quality chamber contains a CLIMPAQ and a set-up for smelling different sources of pollution (Figure 14(a)), the acoustical test chamber contains a sound system with two independently controlled near-field loudspeakers (ADAM Audio A7x). In the thermal comfort chamber, an exhibit is currently running that requires VR equipment (glasses + hardware) and software, a fan (to simulate fresh air when in the virtual environment a window opens) and a construction lamp (to simulate sun radiation when in the virtual environment a solar screen is removed), while in the light chamber a mock-up of the exhibition of Jan Schoonhoven is shown (see Figure 14(b)).

The four test chambers are supported by means of a steal frame, a structural floor and a stairway with railing to get to the first floor. The first floor has a balustrade with a railing. In front of the two test chambers situated on the platform, an outside exhibition space is located for some wider experiments and experiences (currently: a ‘sound shower from Sol4’).

Figure 15. Supply (a) and (b) overflow in one of the test chambers.

Conclusions and future plans

After four years of planning, lobbying, preparing and building, the SenseLab was created and is now available both for studying integral perception of IEQ under different scenarios in the experience room, as well as testing and learning in the four test chambers for air, light, thermal and acoustical quality.

The Science Center, where the SenseLab is located, receives many visitors among which a lot of school children, but also many students of the Delft University of Technology (cc. 22,000 students). It is therefore an excellent location to perform tests with both school children and students in classroom and office-like environments. The SenseLab makes it possible to involve children, but also young adults in another way than via questionnaires or performance tests, for example, through interactive techniques (e.g. using mock-ups, sketches and focus groups), in order to provide more insight in potential causal relationships at individual level, but also insight in the total picture and interrelationships between different environmental parameters and other aspects (e.g. confounders) (Bluyssen 2014, 2016).

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Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Prof. dr. Philomena M. Bluyssen, initiator and creator of the SenseLab, was appointed full Professor Indoor Environment in 2012 at the Faculty of Architecture and the Built Environment, after working for more than 21 years for TNO, a research institute in the Netherlands. She holds a master degree (building engineer) from the Technical university of Eindhoven (1987) and a PhD from the Technical University of Denmark (1990). She has written more than 200 publications in (inter)national journals and conferences. For the Indoor Environment Handbook: How to make buildings healthy and comfortable, she was awarded *the Choice Outstanding Academic Titles of 2010 Award.* Her book titled 'The Healthy Indoor Environment – How to assess occupants' wellbeing in buildings', published by Taylor & Francis in 2014, was awarded the *Interior Design Educators Council 2016 book award.*

Freek van Zeist assisted with the design and construction of the SenseLab. He is currently working at the company TheNewmakers, where he pushes boundaries with the integration of design, engineering and production by the use of CNC digital production technologies. He works on circular furniture, interiors and on disrupting the building industry by introducing new (digital) production methods and integral visions on mass customization. He was a researcher with the chair Indoor environment from 2014 to 2016. He graduated cum laude at the Faculty of Architecture, Delft University of Technology as an architect on transformation of office buildings to dwellings in 2014.

Stanley R. Kurvers, responsible for the contents of the thermal quality test chamber and involved in the creation of the SenseLab, currently is researcher at the Chair of Indoor Environment at the Faculty of Architecture of Delft University of Technology. He has a career in the field of indoor environmental quality since 1978 at the Dutch Governmental Occupational Health Service and various Indoor Climate consultancy companies. His main interests are thermal comfort, indoor air quality and post occupancy evaluation. He also contributed to the development of tools, guidelines and methods for building indoor environmental quality.

Dr. Martin Tenpierik, responsible for the contents of the acoustical test chamber in SenseLab, is an assistant professor of Building Physics and leader of the section Environmental & Computational Design. He completed his PhD research in 2010, for which he studied the use of vacuum insulation panels in buildings. His recent research focusses on: 1) the energetic performance of building systems and whole buildings, with a focus on dwellings; 2) building physical properties of materials (sound absorbers and systems for passive climate control) 3) room acoustics of classrooms, open plan offices and sports venues. He has authored more than 30 journal publications and many conference papers.

Prof. Dr. Sylvia Pont, responsible for the contents of the light test chamber in SenseLab, was appointed Antoni van Leeuwenhoek professor in 2016 at Delft University of Technology, the Netherlands, where she works at Industrial Design Engineering since 2008. In the light and vision labs, part of the Perceptual Intelligence lab, her group works on studies in design, perception, and optics of light, materials, and shapes, and their interactions. She coordinates a Master's course Lighting Design and teaches visual perception and research methods. From 1999 to 2008 Sylvia worked at Utrecht University, Columbia University and Stanford University, on "ecological optics" and the appearance of natural materials and light fields.

Bart Wolters, who was involved in the design of the electrical installation of the SenseLab, is manager engineering at ENGIE Services West B.V. He got his Masters in mechanical engineering at Delft University of Technology in 2004. For several years, he worked as advisor and senior engineer of energy systems and climate systems. From 2012 on he leads teams with multiple engineering specialists in multiple disciplines, electrical and mechanical, to create highly integrated designs. The design teams are able to do a complete design cycle, from conceptual design to construction design.

Luuk van Hulst, who was involved in the design of the HVAC-system of the SenseLab, works at ENGIE Services West B.V. as a senior engineer mechanical installations. He is working in this field since 1988 after concluding the education at 'HTS Rotterdam' with a bachelor degree in mechanical engineering. His main field of work is planning and engineering climate systems (HVAC) for buildings, hospitals and light industry. Last years with extra focus on energy efficiency and sustainability.

Darell Meertins, who was responsible for the planning and structural safety of SenseLab, is the director and owner of Darellsoffice BV. He has more than 25 years of experience in design and preparation work for design and construction of infrastructure. He is a structural engineer, graduated from Delft Technical University. Before he started Darellsoffice BV, he worked for CFE as design and tender manager for eight years, for Ballast Nedam International as project engineer for two years and for Van Hattum en Blankevoort eight years as senior structural engineer. His main scientific interest lies in management of project processes with the aim of achieving an effective and sustainable construction process, based on the principle of life cycle systems engineering.

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