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Teaching comfort

Critical approaches, digital interventions and contemporary choices

Ola Uduku, BK Satish, Gillian Treacy and Yiqianq Zhao

Introduction: what is comfort?

Comfort was defined by Gagge as 'one kind of recognizable state of feeling which doesn't directly link with sensory organs' (Gagge et al., 1967). The human sense of comfort encompasses a person's relationship to their entire internal environment via various sensory feedback systems, both physiological and psychological and including feelings of happiness and health, sadness and pain.

Historically, environmental designers have more narrowly defined comfort as a state of thermal equilibrium where all energy, measured in terms of heat radiation and evaporation, equates to zero, $M =/-Rd +/- Cv +/- Cd - Ev = \star S$ (ASHRAE, 2010). Over the past three decades, the understanding of what is involved in the achieving of comfort has extended well beyond the very narrow limits of the factors in the above equation, derived from ASHRAE standards, based on laboratory experiments in Europe and America, using limited groups of largely Western subjects. The focus in the design of low energy buildings is now on the adaptive model of thermal comfort that derives from the analysis of data from field surveys of ordinary people in their usual workplaces or living spaces. The reported comfort temperatures take into account the extent of the human adaptation of local populations to their seasonal thermal conditions in local climates, environments and economies, also reflecting and typical cultural lifestyle choices in clothing, activity type and so on (Humphreys and Nicol, 2018). Both approaches to quantifying thermal comfort do not take into account other aspects that contribute to localised, or personal, comfort or feelings of well-being.

Environmental design specialists also teach a range of other associated environmental disciplines that contribute to individual perceptions of the environment and its influence on the senses such as acoustics, and the effects of lighting that are also implicitly embedded within a more holistic understanding of comfort from a built environment perspective. The challenge for teachers is how best to incorporate this holistic understanding of comfort into the taught curricula for environmental design, and into a wider matrix for measuring and analysing comfort. The bioclimatic chart diagram as produced by Olgyay and Olgyay (1963) (Figure 31.1) was the first attempt to graphically represent the various

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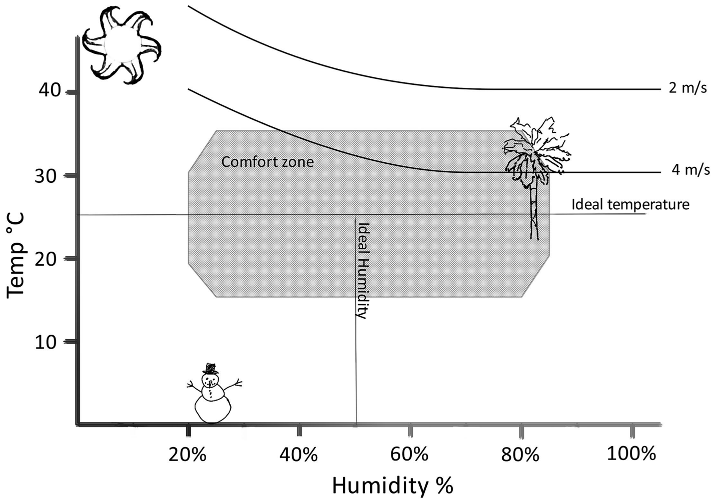

Figure 31.1 Bioclimatic chart diagram (after Olgyay, 1963)

physical factors that are taken into account when designing for thermal comfort; however, the chart does not take into account the acoustic or visual comfort experiences of occupants.

Another area that has been often overlooked in environmental design and comfort teaching is 'health and wellbeing'. However today, for younger students, designers and the general public, the concept of comfort is often associated with issues of health and well-being, presumably because of increasing levels of Sick Building Syndrome in modern buildings and consequent health implications (Ghaffarianhoseini et al., 2018). The COVID-19 pandemic has also elevated concerns about health impacts of building design and occupation to a primary concern about well-being and working conditions, highlighting the urgent need for a more holistic approach to understanding, teaching and designing for thermal comfort, not least to address the growing need for more resilient building, that can keep occupants safe even during extreme weather or health events.

Good design can also lead to the experience of 'thermal delight' (Heshong, 1979) evidenced by personal encounters with sounds that sooth or touch the soul, lyrical light images and also the sensory feel of warmth, or coolness of airflow over the skin as the body becomes more comfortable in a response known as allisthesia (Cabanac, 1971). Can such a palette of sensual comfort be taught in design schools? Might this stimulate greater pedogogic ambitions than simply ensuring that thermal comfort teaching imparts recent building codes to the next generation. The aspiration of holistic environmental design teaching is to enable students to appreciate that comfort encompasses a wide spectrum of issues and influences incorporating the regulatory, as well as the more sensory experience-driven aspects of building comfort.

In this chapter, elements related to a wider understanding, or conceptualisation, of comfort are discussed which the authors have explored and sought to address in teaching design, starting with a revision of the classical definition of comfort, followed by an overview of some of the other environmental design factors that have been explored in design studios, and practical tasks set for student environmental design workshop settings by the co-authors of this paper.

Thermal comfort models

Fanger's predicted mean vote (PMV) measure was introduced in the 1960s to produce a usable method of allocating predicted comfort responses to temperature (Fanger, 1967). Its value has been challenged in recent years by many (Nicol et al., 2012, pp. 44–51), and significantly by Chang (2016) as being predicated on data gathered from only a certain section of the Western public whose experiences do not represent those of most who live in the regions that the PMV data represents. Furthermore, the Fanger PMV method only describes sensation on a seven-point scale, and not perception (Fanger, 1967). It should also be noted that the Fanger PMV analysis focuses on comfort votes to be utilised in designing and predicting mechanical heating and cooling needs for buildings, i.e. it focuses on [dis]comfort needs, and its remedy is mechanical air conditioning, the benefits of which are clearly laid out in air-conditioning performance tables. This very limited and prescriptive 20th-century view of comfort has changed considerably over the last 20 years, and today much thermal comfort research focuses on creating comfort models that can be used to best determine what materials and design approaches can be applied in order to achieve 'resilient' sustainable buildings for the 21st century. This focus ~~in~~ low energy design goes back to traditional design methods where passive cooling, using minimal mechanical systems, and employing natural ventilation and locally appropriate passive design features and opportunities. Architecture designed to take advantage from what the local climate offers needs to be underpinned by the much more flexible comfort limits provided by the 'Adaptive Comfort Method'.

Well-designed low energy buildings using these adaptive thermal comfort principles are also more sustainable in their use of materials, and resilient in energy use. This is because the buildings themselves take an active role in the search for indoor ~~comforts~~. Building ~~Elements~~ such as walls and floors act as heat sinks and stores for heat and coolth that are harvested at different times of day and year at different temperatures, while still providing comfort. A house in winter might be considered agreeably warm at 190°C, or cool in summer at 270°C or yet under PMV-based standards, these homes fall out of the comfort zone and require energy and cost expensive air conditioning to meet the standards. Buildings that rely on mechanical systems to provide acceptably comfortable temperatures indoor are more likely to fail during extreme events because the system in use does not rely on the performance of the building itself to provide comfort. The introduction of ~~a~~ passive design features enables buildings to be able to run for significant periods of the year employing only passive, free natural energy, minimising the need for non-renewable energy sources, thus significantly reducing the greenhouse gas emissions to keep people safely comfortable for longer, even when grids fail or energy costs become unaffordable.

This adaptive model of thermal comfort as described by de Dear (2011) and Nicol et al. (2012) focuses on reporting local thermal preferences via surveyed comfort votes; it does not however take into account the sensations of sensory delight, or 'Allisthesia'.

Allisthesia

Within the human brain and its physiology is inbuilt an extraordinary feedback system that rewards people for taking actions to become more comfortable. It is an important adaptive feedback mechanism, and the rewards take the form of sensory feelings of thermal well-being and delight. Thus for air movement within an enclosed space, people who feel warm would prefer more air movement and people who feel cold would generally prefer less air movement (Parkinson and De Dear, 2017). Tourists often choose different climate conditions for holiday and vacations, due exactly to the difference in temperature that enabled them to reward themselves with small doses of delight, when they dive into the pool, or sit in a cooling breeze by it, or warm up in front of a fire after skiing. Apart from the deep appeal of new views and experiences, people revel in the delight of related thermal stimulants and new sensual pleasures. The feedback system underpinning these responses is called thermal allisthesia, and was also characterised as individual internal ambience (Cabanac, 1971; Hechong, 1979; De Dear, 2011).

Parkinson and De Dear (2017) established that the contrasting relationship between local and global skin temperatures trends enables positive thermal pleasure. Brager et al. examined the quality of indoor air movement to advance the understanding, and use of alliesthesia by designers (Brager et al., 2015). However, thermal comfort continues to be currently taught in its engineering-focused PMV form, focusing on measuring the elements which contribute to thermal comfort equilibrium, air flow, humidity and forms of thermal heating, PMV scores and a concession to the use of adaptive thermal comfort as a moderating category to final results.

Studies relating to alliesthesia tend to combine physiological (objective) and psychological (subjective) measures. Son and Chun (2018) have studied the correlation between psychological and physiological responses to comfort, demonstrating that electroencephalograms (EEG) can be used to measure both psychological and physiological responses, for instance, for feelings of alliesthesia. However, the complexity of this research and its non-incorporation in standard comfort measurements means that it is often not taught to students at undergraduate level. An advantageous increased awareness of allisthesia in the building construction field would be achieved if this theoretical concept was incorporated into environmental design teaching at undergraduate level.

Environmental design teaching

In the field of environmental design teaching and research, a paradigm shift occurs in how we understand and apply ideas of thermal comfort in design. International, builder-focused certification systems to assess the performance of buildings in relation to their impact on the environment and resources have proliferated over the last decades with the environmental assessment systems such as BREEAM, LEED and Passivhaus, and the Well Building Standard being used for high-end buildings, in addition to the more engineer- and builder-focused building regulations and standards in common use nationally. As buildings are increasingly marketed on their environmental credentials, public appreciation and understanding of the issues at stake have grown. It is widely acknowledged that climatically well-designed, low energy, buildings are good for the climate, and can promote better health and well-being of occupants. Well-being is, in effect, a proxy name here for holistic comfort. Designers are moving to looking at comfort through a person-centric lens, rather than a building-centric one as it is viewed by engineers. A strong, evolving theme in design schools is the interest now shown in sustainable and environmental issues, as individual occupant's health and well-being are prioritised, as a new balance is sought through trade-offs between building performance and the well-being of occupants that benefits both.

Well-being

Our sense of well-being can be connected to the idea of 'spirited wellbeing' or 'spiritus'; the interrelated notions of air, breath and spirit are all terms that have their origin in the

Greek 'pneuma' (Negar, 2020). Defined as 'breath' or 'wind' as a simultaneously material and immaterial phenomenon, it is understood to be a life-giving and an inspirational medium to which we are elementally connected (Abraham, 2013; Böhme, 2017). An interior environment creating 'comfort' for inhabitants is achieved through the careful balancing of the interior with the external environment to achieve a space that promotes a sense of well-being or 'spiritus' (Abraham, 2013).

This holistic understanding of well-being can only be achieved through a rigorous application of key environmental design concepts from macro to micro scale, starting from our external environment, our built environment, and permeating into the interior spaces that surround our diverse human conditions and preferences. Emmons and Frascari in Kenda (2006) have described this surrounding environment as an opportunity for a 'meaningful plenum' rather than an ill-considered 'irrelevant vacuum'. This surrounding space or architectural 'biosphere' (Montiel et al., 2020) can help support our health and well-being if procured through informed design aspirations and innovations. The interior of any architectural space is defined as part of the built environment being in direct mediation with the space occupants and constituting the nearest area for their activities. It therefore directly influences our health and ~~well-being, and stimulates our behavioural patterns~~ (Celadyn, 2018). Comfort can be taken from, and provided by, not only the thermo-regulatory system, or the sensual delight offered by allisthesia-triggered responses, but also from the spiritual peace or torment that can be derived from a building. Much comfort is also derived from an uplifting of the spirits in an interior space, with mental and physical health impacts following, as evidence by the succour provided, over the centuries, from quiet times spent in spiritual spaces.

New design approaches needed

The emergent global concern about climate change offers an opportunity for revitalised interest in the environmental performance of buildings, and an urgent need to re-assess, inform and educate students on how to move on, from the environmentally damaging cultural design norms that shape so many modern buildings and dominate much of the discourses in the architectural press. Students must be taught how to respond to current issues related to climate over-heating, largely by focusing on natural climatic design principles, grounded in local vernacular building examples, and cultural experiences of comfort. A re-framing of the empirical underpinning of our understanding of 'comfort', within the educational system, with its many interrelated relationships to occupied environmental conditions is necessary to also shift and inform client behaviours and understanding too.

To achieve such ambitious aims, new approaches to the teaching of building comfort are needed, supported by new teaching tools and methods, and it is these that are now discussed.

Tools for teaching

The traditional use of analogue tools within architectural design education like models and sketches valued the skills and craftsmanship of drawing and physical models to measure, represent and understand our spatial environmental ambiance. This physical, 'hands-on' approach (Pallasmaa, 2009) is known to instil a haptic understanding of design. Haptics is the science and technology of transmitting and understanding information through touch, opening a door for the appreciation of the less tangible elements of environmental design such as temperature, sound and light. Simulation and computer modelling now dominate in design studios despite the fact that digital tools can provide efficient, precise prediction, and numerical verification of architectural interior space through 3D computer modelling and calculation software models only model what they model, omitting any design dimensions related to the sensual experience of buildings in early design stages (Uduku and Treacy, 2014).

It is often at the early stages of designs that major climatic decisions and mistakes are made. The numerically complex and sophisticated metrics produced by software regularly ends up being used to sell solutions to clients. These solutions are often already deeply flawed due to the following:

a Poor understanding of the basic tenets of climatic design by the designer or client.
b The 'black box' assumptions written into the software, often focusing on mechanical conditioning systems, as engineering solutions to comfort problems, and not considering passive design solutions such as natural ventilation or thermal storage systems made available by good passive design.
c The flawed assumptions input into the simulations in progress, either through poor training and understanding, or in order to skew the final performance results to enhance the appeal of a design. It is very difficult ~~for training~~ designers, who have little experience of how a line on the screen looks or feels when built, to imagine how it will affect the senses of occupants and breathe its spirit into people experiencing it.

How will those lines translate in spaces to positively affect a person's health and well-being? The experience of a future building is difficult to grasp for the uninitiated or non-specialist practitioner or design student. How can environmental design tutors teach students how to understand and apply holistic comfort principles into their designs, when they are not incorporated into the standard simulation design tools they routinely use on their courses?

Emerging environmental design pedagogies

Such issues and challenges were the subject of a series of pedagogical workshop studies held within the technology and environment undergraduate courses at the University of Edinburgh, Edinburgh School of Architecture and Landscape Architecture (ESALA) and the School of Design over a period of ~~two~~ years during ~~2017–~~2018. Their deliberations are summarised below and demonstrate the success of combining the physical, experiential, sensual learning of environmental principles with numerical and digital modes of learning to provide insights into the limitation and opportunities of how they connect and possibly translate into better design for the comfort and well-being of occupants at a personal level.

Key findings from our pedagogic comfort workshops:

1 Learning by Experience: The importance of learning how the comfort numbers are actually experienced in the real world.

Students were asked to evaluate the space within a newly built church building for congregational worship, by visiting it and recording the environmental conditions within the space using real-time sensors (Edenapp) and physical measurements (Figures 31.2 and 31.3).

Figure 31.2 Case study building exterior view – St Albert the Great chaplaincy, Edinburgh (G. Treacy)

Figure 31.3 Student field visit to St Albert the Great chaplaincy, Edinburgh (G. Treacy)

2 Learning by Listening: Students developed an appreciation of the environmental needs of building users (possibly clients) both as individuals and as a group of people who customarily inhabited the space. The students were invited to meet a range of stakeholder associated with the building, as well as its original client who co-developed the brief for the building with the designer. Both gave a realistic overview of how the building functions on a day-to-day basis, as well as an assessment of the comfort and experiences of well-being associated with its operation over days and weeks and seasons.

   These visits and discussions were held as brief, on site, workshops, but were nonetheless useful in developing an understanding of environmental conditions, and the 'comfort' needs and expectations of the building users, and the success, or lack of it, produced by the as-built interior systems involving heating, cooling, acoustics and lighting on the behaviours and health and well-being of the occupant's experience of the as-built chapel.

3 Learning by Playing in design development: Students developed physical models of the visited space and used mobile app sensors (Edenapp, PhotoLux, Sound Meter and Sound Spectrum Analyser) to explore, play with and record the changing environmental conditions in simply affected changes on the model to manually optimise holistic comfort conditions within the space. Students gained an enormous amount from testing the physical model as it was quickly and easily possible to deconstruct the interior space and facade and rebuild, re-test and adjust the environmental conditions while re-assessing in real-time conditions.

4 Learning by Modelling: In parallel, two groups of students were set the task of using simulation to optimise the comfort benefits of a design. Test Group 1 (TG1) developed and collated data from testing a digital architectural model of the same chapel space. TG2 did the same for a different space, both using the simulation model IES VE.

The results were hugely telling. TG1 were able to critically reflect on the data input and output from their IES VE analysis, and deal intelligently with the associated design challenges, having prior knowledge of the behaviour and outcomes of the real building they were modelling. They were quick to understand the context of the modelled conditions and adjust any anomalies within the digital model and enhance the final design using that knowledge. Additionally, after reflection, they were able to suggest exploring original, alternative design solutions to adapt the design to suit a change in environmental priority or ambience.

TG2 had difficulties. They used an alternative digital model, a space that they had not previously visited or measured, and struggled to read and understand the output figures produced by the software for the given 3D model. This was not apparent initially, as both groups could produce figures and findings that were graphically impressive, with convincing narrative, but few in TG2 understood how they might revise the given values applying design changes to their the model, to address alternative building occupant needs and/or environmental conditions. With limited understanding of how the building worked in practice, or the key elements influencing the resultant environmental values, it was nigh on impossible for them to propose constructive optimisation pathways.

The Edinburgh environmental teaching approach

Testing these different pathways to the design of holistically comfortable buildings highlighted the importance of not only using a variety of tools to support design choices to suit emergent environmental priorities when haptic associations are possible. It also showed that the tools should be used in a logical order so that students understand from early on the lessons that can be learned from measuring real buildings in real time, reproducing their environments through physical models, and listening to and learning from first-hand experiences of their everyday existences. Only then should this understanding be built on by teaching students to learning more about buildings by simulating virtual environments and exploring What-If design scenarios using them (Treacy, 2019). Students have to know in the first place what they are modelling, and why, to be able to eventually design competent, if not excellent buildings.

This approach to teaching environmental design thus relied on both local engagements, with directly encountered and collected data, a working knowledge of what both the measurement tools and hand-held apps produced, and also, finally, a working understanding of the meaning of the digitally delivered data sets, via the IES thermal model, which had been specially tailored to respond to the requirements of UG teaching of environmental design. The results of the test groups showed clearly that these new pedagogic techniques worked, with the group who combined the interpersonal experiences to inform and lend meaning to the models being particularly successful.

The importance of timing in comfort teaching

Due to the clear limitations of most modern design tools and approaches when used to produce genuinely low energy and holistically comfortable buildings, the Edinburgh experiments showed that a sensible process of teaching students to understand comfort needs to involve much more than the simple ability to simulate a building. The following process of teaching students about comfort is proposed.

Constraints on the new approach

Traditionally, the measurement tools are expensive and require proper calibration and maintenance over time. The upfront costs of equipment already make many schools reluctant to invest in physical measurement tools, while being quite happy to spend what it takes to install the latest computer systems. This constitutes a serious constraint to the proposed HCT process in Table 31.1. To overcome this reluctance and reduce costs for a comprehensive thermal comfort data collection tool, Zhao developed an open-sourced extension for EdenApp in his

Table 31.1 The holistic comfort teaching (HCT) process

1	Learning through experience – real-time: Students are introduced to comfort senses & tools in real environments in real-time. Through active engagement, students link human sensual perceptions experienced both individually and as a group to real spaces for future reference.
2	Learning through listening: Students taught to field human responses in real buildings and seek comments on designs by stakeholders.
3	Learning through play – physical scaled models: Haptic exploration of modelled environments affected by building shell and interior in local setting/site. Exposes the 'workings' behind numerical comfort values and the resulting physical experience.
4	Learning through play – digital models: Digital exploration of modelled environments affected by climate, building shell and interior.
5	Learning through adapting – building models: Students adapt physical and digital models to test alternative solutions and understand ranges of values and factors influencing results.

research which focused on personal comfort modelling and measurement in student accommodation, using a combination of both sensors and digitally recorded thermal comfort votes (Zhao et al., 2018) (Figure 31.4).

Both the EdenApp system sensors and mobile application make it easier for researchers and graduate students to collect person-level data for a minimal cost, rather than worrying about expensive equipment spends and costs for the collection of in-person manual votes (Figure 31.5). Meanwhile, the open-source hardware and hardware community provide

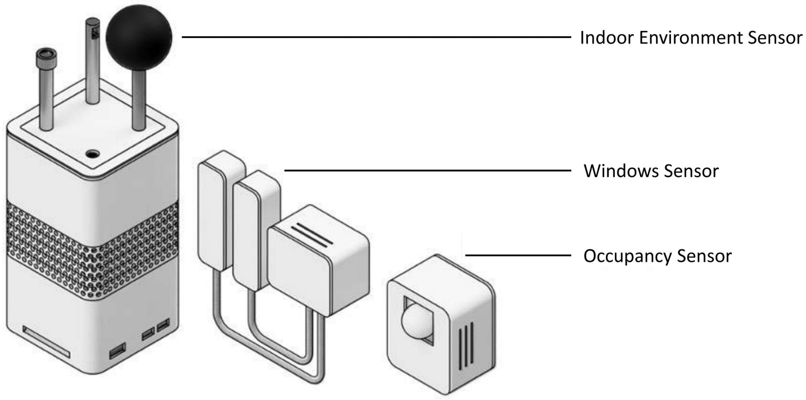

Figure 31.4 EdenApp thermal comfort sensors (Zhao et al., 2018)

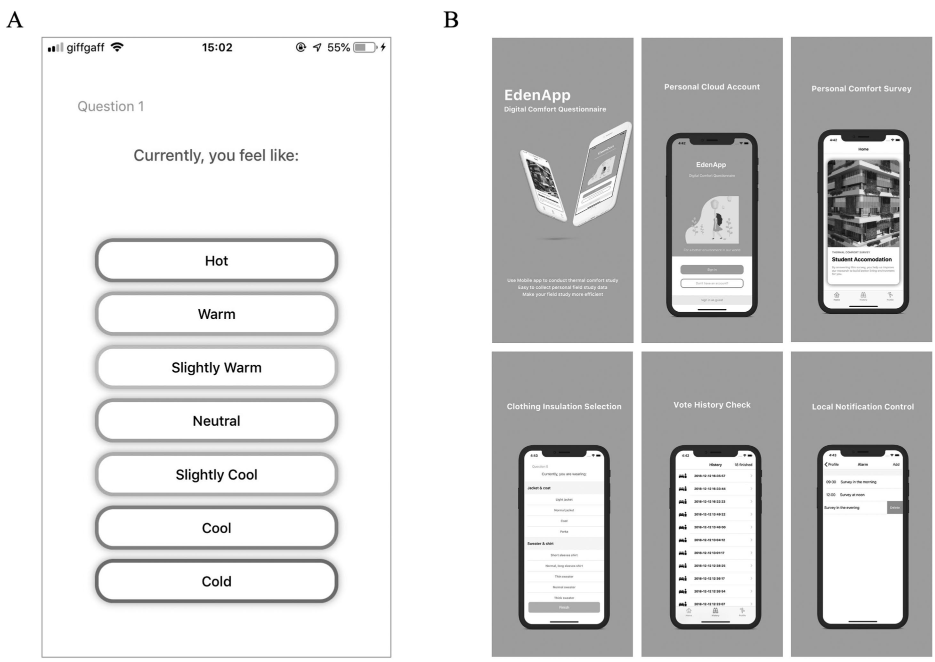

Figure 31.5 EdenApp thermal comfort mobile application (left side shows in-built survey questions; right side shows the overall workflow of the mobile app) (Zhao et al., 2018)

strong user support and the opportunity to add more variables. This flexibility offers the opportunity to increase the diversity of measures by which comfort is holistically evaluated and integrated into design teaching and in practice.

Future design teaching trends

Based on the student teaching case studies discussed, and Zhao's development of digital tools for his field research analysis, there are three contemporary teaching trends that can be identified as potentially influential:

Software trends and development

The 21st-century environmental design teaching process relies strongly on digital software and teaching tools. SketchUp, Rhino, AutoCAD and Revit are amongst the key software used for constructing models for the visualisation and analysis of environmental design interventions. Software however can have an unpredictable lifespan, depending on business considerations such as levels of use, demand and professional popularity. Environmental analysis and teaching tools can be very 'niche'. Thus, due to the slowing public use and demand for a leading environmental tool, the software firm Autodesk shut down the excellent environmental analysis programme Ecotect in 2015 and Flow Design in 2018. Furthermore, many of the software programmes require specialist-environmental engineers to use them well. Thus, the IES programme used by many design students had to be redeveloped and simplified to an IES Lite version by Uduku and Treacy for use by students.

Experience indicated that it is likely that software choice is likely to become student-specific as future students are likely to seek out their own choices and combinations of suitable software for their own environmental analysis. The speed and vast range of software now available mean that educators are unable to have a full knowledge of what exists in the market place, but instead seek to advise and guide students on their software choices and, crucially, provide students with an understanding of the metrics and related numerical figures underpinning the input and output values from any environmental analysis software.

The link of software to workflow and BIM processes in the practice-based design work is also an area that often needs resolution. As there is not a common language defining workflow processes, often design schemes are fragmented as students struggle to apply environmental design analysis rules they have learnt to business design systems software that do not align with university software systems.

It is therefore necessary for educators to clearly understand the opportunities and limitations of mainstream software, and regularly collaborate with architectural firms to ensure there is a shared understanding of workflow systems. This does not mean that student training is limited to the use of only specific industry-aligned software. Instead, it means that there is a need for educators and professionals to have a better joint understanding of the pros and cons of the various systems software that are available and thus be better able to guide and specify software that is both efficient and works across educational and professional practice platforms. The Edinburgh exercises in exploring the role in comfort in design teaching highlight the limits of modelling in this field and the need to understand when and where simulation has a role to play in the design of holistically comfortable buildings. Students need to fundamentally understand the technical, the psychological, sensual, health, welling and spiritual foundations of comfort to be able to eventually integrate them into their design decisions, regardless of which simulation models they finally use to describe the form and fabric of the buildings they work with in practice.

Comfort education, and net-zero carbon teaching

Climate change is a major challenge for architects because the built environment is a major source of CO_2 emissions globally. In 2020, the Royal Institute of British Architects, RIBA, published its 2030 climate challenge principles and goals, in order to encourage the profession's role in accelerating the transformation of the building environment to achieving net-zero carbon targets in time. This urgent need to transition to net-zero design not only highlights the importance of carbon calculations for buildings, but also adds a complication because now, to focus on an early design stage environmental analysis, calculations must now include whole life building carbon emission calculations.

In the UK, the RIBA has begun to address this expanded environmental responsibility for architects, through its series of free CPD programmes on zero carbon design available to all its members, but the training provided has inevitably reflected Business-As-Usual (BAU) understandings and priorities of those who co-produced the CPD programmes, using currently available simulation approaches. The Edinburgh experiments have highlighted the fundamental need to address the knowledge base, and methods of teaching and learning deficits currently espoused in design schools in relation to the creation of holistically comfortable buildings. Engineering students are inculcated with over-simplistic, and flawed, comfort criteria based on, for instance, the steady state comfort model promoted in Fanger's (1970) PMV-PPD methodology that is simply designed to produce one or two numbers that engineers or BIM systems can set thermostats to. The Edinburgh experiments have shown that in order to design buildings that stand the test of time, real human beings need to be put into the design equations, and the holistic comfort teaching process has been proposed for early design stage design teaching to enable students to have a good chance of being trained beyond the current, flawed comfort opportunities available in BAU design models. The days when it was considered an acceptable architectural education outcome to simply produce proficient simulation experts or CAD ~~Monkeys~~ must end if our societies are to be able to produce genuinely comfortable 'Low Carbon' buildings in practice.

Teaching methods in a post-COVID world

The COVID pandemic forced all university teaching to be delivered online, so much design teaching was presented in case study modes, through online learning platforms. Feedback from students in many UK institutions suggested that many were unhappy with the immediate transition to online materials and teaching provided as prior planning had not been possible. However, as lockdown eased in most UK universities, some face-to-face tutorials took place, although the majority of the 2020–2021 academic year's teaching was undertaken online.

This is part of the major change to higher education teaching and pedagogy worldwide. Universities in the UK have now invested significantly in online delivery and for Generation 'Z', engaging with online education has become a fundamental part of their university educational experience. As a result of this wholesale move to digital online teaching throughout the COVID-enforced lockdown, the discussion of the development of 'digital teaching delivery' based around the use of digital tools has become a significant opportunity for future environmental design pedagogy within an international and global context. The Edinburgh study showed how much better students performed as designers further to prior learning using experiential tasks and measurements in a real building with real occupants. The challenge now comes to devise teaching and learning methods so that the same level of experiential learning can be achieved by individual students, alone in their own homes.

The challenge is clear: how can we make the online learning experience close to, or better than, face-to-face teaching? The development of EdenApp as a digital tool shows one way forward. It successfully gives the control back to the student to enable them to decide when and where they want to learn. Combined with low-cost sensors, students can measure different environmental analysis variables (heat, humidity and air flow) in their own time, in personal surroundings and contexts such as their study bedrooms or other spaces near where they live or visit. They can learn to sense and feel the world they occupy, so heightening their innate understanding of comfort in the round, and share their unique learnings with their peers, allowing, for instance, comparisons, and local and classroom discussions about what differences might mean. With the personalised sensors, students are also able to collect enough data to calculate their personal thermal sensation levels, comparing predicted Fanger PMV-PPD comfort levels with their real-time sensor-calculated vote. This thus allows students to have a direct ability to measure, report and reflect on to build an understanding of adaptive comfort in reality, in the different climate zones, that they might encounter in their future working lives. The aim is to educate a new generation of sentient comfort designers, and the tools already exist to do that whether for face-to-face or remote learning programmes.

Conclusions

There are many popular theories developed as to what design students should be taught during their education. Today, the onus is firmly put on training designers to be able to create zero-carbon building in practice, not simply as modelled, but as built. In the face of a rapidly heating world, the need is not for merely 'sustainable buildings', measured in rating systems and dashboards of indicators compared in black box systems of embedded interests. The balance has tipped firmly in favour of seriously reducing energy consumption in buildings. At the heart of related future-proofing design challenges lies the need to keep building occupants comfortable at an acceptable environmental cost. To do this, it is critical that all design students should be taught about the fundamentals of holistic comfort, and a five-step HCT process has been proposed to do just that.

Because of the over-riding importance of comfort in low carbon buildings, it should be a priority to graduate comfort-literate students from all schools of design from now on. Schools may find it useful to:

- a Understand that comfort is a multi-dimensional phenomenon.
- b Give students the tools to explore the many dimensions of comfort.
- c Educate them in the importance of their own sensory experience and learning processes.
- d Teach students to listen to building users to understand more on comfort.
- e Enable students to link heart and mind and learning by playing with physical models.
- f Use simulation only for what it is good for; in optimising opportunities, not defining them.
- g Teach students to 'ground truth' solutions by exposing their designs to potential users for comment.

Teaching in a rapidly evolving world must be about helping students to be flexible in their design approaches, and how to critically learn about the environment through engaging, experiencing and understanding situations as they change. Students must not be hampered by only being taught ridged, and outdated, 20th-century tools, models and comfort approaches. They must be taught to trust in their own instincts and abilities to design for a different future. The HCT process is presented above by which the Edinburgh team introduced students to working experientially, using contemporary tools for learning during the development of their designs, a process that worked very well. To be of relevance and use, in the very challenging future we face energy and resilience issues, 21st-century environmental design education will need to prioritise and promote the teaching of comfort to all students, using holistic teaching methodologies, to matter and make a real difference.

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