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# A holistic, multi-level analysis identifying the impact of classroom design on pupils' learning

Peter Barrett*, Yufan Zhang, Joanne Moffat, Khairy Kobbacy

*School of the Built Environment, Maxwell Building, University of Salford, Salford M5 4WT, UK*

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A B S T R A C T

The aim of this study was to explore if there is any evidence for demonstrable impacts of *school* building design on the learning rates of pupils in primary schools.

Hypotheses as to positive impacts on learning were developed for 10 design parameters within a neuroscience framework of three design principles. These were tested using data collected on 751 pupils from 34 varied classrooms in seven different schools in the UK. The multi-level model developed explained 51% of the variability in the learning improvements of the pupils, over the course of a year. However, within this a high level of explanation (73%) was identified at the "class" level, linked entirely to six built environment design parameters, namely: colour, choice, connection, complexity, flexibility and light.

The model was used to predict the impact of the six design parameters on pupil's learning progression. Comparing the "worst" and "best" classrooms in the sample, these factors alone were found to have an impact that equates to the typical progress of a pupil over one year. It was also possible to estimate the proportionate impact of these built environment factors on learning progression, in the context of all influences together. This scaled at a 25% contribution on average.

This clear evidence of the significant impact of the built environment on pupils' learning progression highlights the importance of this aspect for policy makers, designers and users. The wide range of factors involved in this holistic approach still leaves a significant design challenge.



## 1. Introduction

The multi-sensory impact of built environments on humans is a complex and current issue as illustrated by some recent papers. For example, Bluyssen et al. [1] highlight the importance of complex interactions in understanding indoor environmental quality (IEQ). They suggest the individual factors "… can cause their effects additively or through complex interactions (synergistic or antagonistic)" (p. 2632). Huang et al. [2] reinforce the interactive nature of IEQ, stating that "Physical environmental parameters are all interrelated and the feeling of comfort is a composite state involving an occupant's sensations of all these factors" (p. 305). Cao et al. [3] state that "Researchers have realised that people's discomfort is usually not determined by a single factor but instead reflects the integration physiological and psychological influences caused by many factors". Kim and de Dear [4] argue powerfully that there is currently no consensus as to the relative importance of IEQ factors for overall satisfaction.

Within the challenging context, this study set out to take a multi-dimensional, holistic view of the built environment within which humans (pupils in this case) live and work (study in this case) and sought to discover and explain the impacts on human well-being and performance (improved learning in this case).

The main aim of this study was *"to explore if there is any evidence for demonstrable impacts of school building design on the learning rates of pupils in primary schools"*. This is a powerful focus, given the availability of meaningful human performance metrics, the fact the pupils spend most of their time in one classroom and the societal importance of maximising pupils' achievement.

## 2. Theoretical approach

### 2.1. Overview of planned methodology

Studying the holistic impact of built spaces on people "in the wild" is a complex problem. So, this project draws particularly from

* Corresponding author. Tel.: +44 0 7836 704 743; fax: +44 0 161 295 4587.
*E-mail addresses:* p.s.barrett@salford.ac.uk (P. Barrett), y.zhang2@salford.ac.uk (Y. Zhang), k.a.h.kobbacy@salford.ac.uk (K. Kobbacy).

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the methodological experience of four key studies (which when mentioned below will be indicated as A, B, C or D):

- Zeisel et al.'s [5] study of the holistic impact of care facilities on Alzheimer's patients (A)
- Ulrich's [6] focused study on the impact of views of nature on hospital patients (B)
- Heschong Mahone's [7] studies of daylighting and its effects on pupil learning (C)
- Tanner's [8] study of school design (D)

The core element of this study was an expert assessment of diverse classrooms using an Environment–Human–Performance (E–H–P) model (A) that allowed the measurement, and so assessment, of built spaces and their human impacts. The survey instruments and "indicators" (A) were carefully trialled. The sample of schools was identified to provide a diverse sample of school types and sizes. Further diverse classrooms were identified within each school, in terms of their physical characteristics (orientation, level, size, etc). This provided the basis for the calibration of the E–H–P model. The theme of diversity in the spaces sampled is important to provide maximum opportunity for the impact of the physical factors to become evident (A, B, C). The decision was made to pursue a hypothesis driven approach so that the aspects of the model displayed logical, as well as statistical, relationships. This avoids the problem of strongly overlapping categories (D).

Alongside achieving diversity in the main independent variable being studied (the physical spaces), there were the issues of accessing consistent dependent variables across the whole sample and measuring (C) or controlling for (A, B) other independent variables. Focusing on the choice of dependent variables first, discussions with educational experts within Blackpool Education Authority were very valuable (C). The measures that are available for primary school pupils, and are consistently used across the UK, are rooted in regular teacher assessments of individual pupils against a National Curriculum Assessment Framework that defines "levels" of attainment. This data is, in the case of Blackpool at least, independently moderated via a sample of 25% of pupils. Levels of attainment for pupils are assessed for Reading, Writing and Mathematics. The effort and expertise that goes into these assessments far exceeds anything the project team could replicate and the measures are well known and understood by practitioners in the education and other sectors. Thus, the decision was clear that these measures should be used if they could be accessed.

The assessment of the impact of the built environment on pupils' performance is complicated by other significant independent variables. The risks to achieving the former were mitigated by the explicit inclusion (or controlling out) of the major additional factors (A, C) in the analysis. The main issue is variability amongst the pupils themselves across classrooms/schools, but was addressed (C) by focusing on progress within a given year, so self-calibrating for variability amongst the pupils themselves. This then opened the opportunity to use entry level of achievement/age which is thought to determine quite a large part of progress achieved and so would sweep in issues of individual ability and some effects of social economic background. Anonymous individual data was collected, including information on gender so that suspected gender differences could be tested. Other school factors are known to have an impact. Physical aspects will be factored in as measurable E–H–P variables, but this leaves elements such as the quality of the teachers, and the general school ethos (C). The identification of groups of pupils in classes and of groups of classes from discrete schools, provide potential ways to provide an analytical way into assessing these aspects using multi-level modelling (see below).

Bringing this all together, the combination of independent and dependent variables studied is summarised in Fig. 1.

### 2.2. Development of an environment–human–performance (E–H–P) model

An holistic perspective of the multi-sensory impacts of the built environment was operationalised via the hypothesis that the

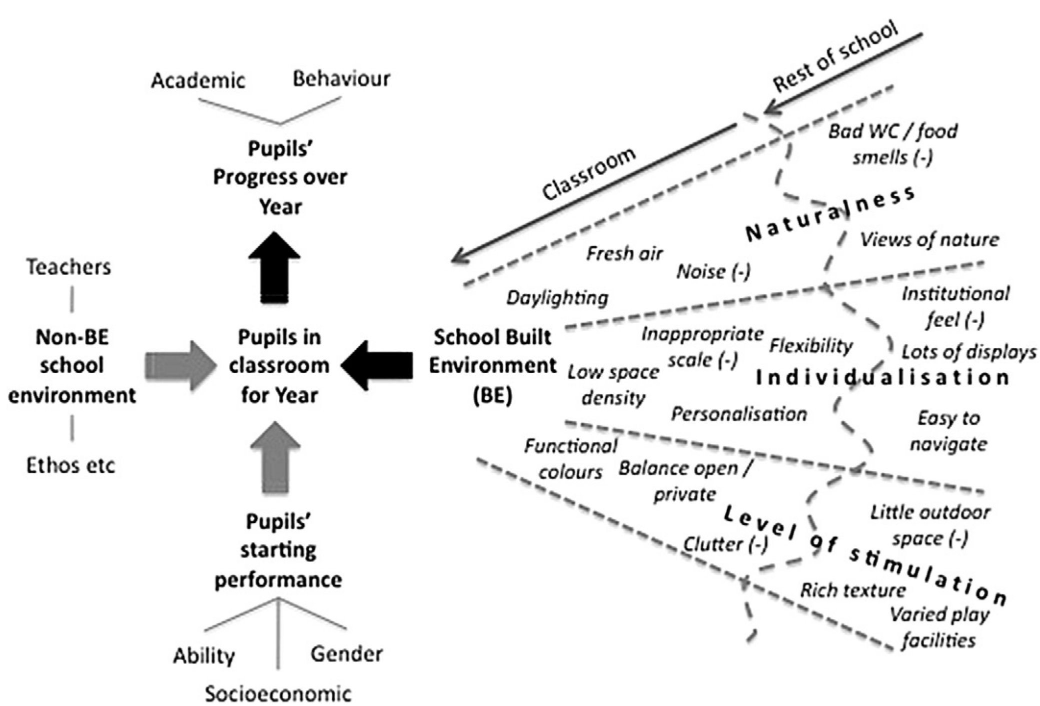


**Fig. 1.** Overview of HEAD research design (with examples of BE factors).

characteristics of the brain's functioning in synthesising sensory inputs highlights the importance of three broad design principles concerning our environment, namely: naturalness, individualisation and the appropriate level of stimulation [9]. In this case these relate, respectively, to: our basic animal demands, the needs of pupils in particular and the implications of the school-learning situation. This broad framework was used to guide the selection of the physical dimensions to be measured, working within the rich context provided by the multitudinous focused studies available in the literature [10], plus a range of school-based post occupancy evaluations [11] and surveys of pupils' and teachers' views [12,13].

The above framework was further developed in this study by taking 10 design parameters [10] and linking each of these to one or two indicators from the literature reviewed and the fieldwork experience of the team. After the site visits and careful reflection, 37 factors were identified to underpin the measurement of the indicators and so the design parameters. A 5-point scale was used in each case to indicate the degree to which it was thought the factor in that classroom would support a pupil's learning activity, e.g. 5 = very good; 1 = very poor. Table 1 summarises the hypothesised design factors thought to impact on a pupil's progress in learning.

## 3. Methods

This covers school/classroom level first and then pupils. It finishes with a description of the multi-level modelling strategy employed.

### 3.1. Schools/classrooms

Blackpool Council supplied access to 10 schools, of which eight were typical mainstream primary schools, with two special schools. For this analysis the focus was on the eight "typical" schools, although in fact one dropped out part way through and so this study actually uses the data from seven schools. All of the schools studied have their own unique features in terms of school site and buildings. Site and floor plans were provided by Blackpool Council. These allowed a clear understanding of each school's location, size, orientation and layout before the fieldwork started.

The focus was on Primary schools, which all met the following criteria.

- Purpose-built public schools for primary education.
- A physically distinct site area with clear boundary condition.
- Dedicated outdoor and indoor facilities.
- Standardized assessment (tests) taken by all pupils.

Table 2 summarises a range of characteristics for the schools and shows a good level of variety across the sample, which should facilitate a meaningful analysis.

The fieldwork was progressed in a similar manner for each school. Two visits were made. The initial visit included an interview with the head (deputy head), explaining the purpose of the study and procedure of the investigation. The head teacher then gave their informed perspective on the general background to the school and also crucial building environment features. Then an accompanied walk-round of the building also provided a further understanding of the school and classrooms.

Based on the information collected at the initial visit, seven classrooms were selected for their diversity, including covering a range of pupil ages. These classrooms became the focus for the second visit. A task list was prepared for each classroom assessment, including three parts:

(a) Observation – space configurations were recorded with a detailed classroom drawing showing, e.g. layout, display, lightings, floor covering, colour, viewout, window (opening) size and position, etc.
(b) Measurement – basic physical parameters of the indoor environmental information were measured, such as lighting level, temperature, noise level and $CO_2$ level. This was a spot check for any extreme aspects of the rooms. Room height, window height, furniture and fixture size are also measured in association with the classroom assessment.
(c) Interview – teachers in each classroom were interviewed with the aim of exploring complex feelings, beliefs. The interview focused on the sensory comfort, e.g. temperature, glare, noise, smell size and storage space. This was an opportunity to gauge any likely variation in the experience of the spaces over the cycle of the whole year.

Based on the record created from the above information, an expert assessment was made by the researchers across the 37 factors identified above in the E–H–P model (see Table 1). Some classrooms had to be excluded owing to gaps in the pupil data (see below), so that 34 classrooms were included in the final analysis. Table 3 shows the difference between these classrooms with regard to their E–H–P design parameters. Generally, no single classroom received consistently high or low scores on all its environmental characteristics. However, there are classrooms that have relatively high or low averages.

This variation in the sample data should facilitate analyses of the impacts of the different design parameters on the dependent variable of pupil learning rates.

### 3.2. Pupils

In principle the data about pupils belongs to the pupils and so a non-contentious process was carefully designed with Blackpool to gain their (parents) informed consent via the chosen schools. In this way Blackpool council supplied data on 1419 pupils across 47 classrooms in the seven schools studied on the following measures.

- A pupil's TA start level for reading, writing and maths.
- A pupil's TA end level for reading, writing and maths.
- Actual age – this is the pupil's age at the start of the academic year (displayed in months).
- Month's age – this is the number of months they have been at their current age at the start of the academic year. For example a value of 0 means they had their birthday in the last month.

A TA level is a measure given to a pupil to assess his or her progressing through school. The TA levels are not measured on a continuous scale. A primary school pupils can be awarded with the lower level P scale, or a higher level of 1–5, which can be split into sub-levels a, b or c. However, these levels can be converted to an equivalent point system (see Table 4), so that the pupils are measured on a continuous scale.

Table 5 provides descriptive statistics of the TA points pupils were awarded at the start of the year totalled for the three subjects, the total points awarded at the end of the year and the total improvement points over the year studied. Some pupils were awarded a lower number of points at the end of the year compared to the start. Pupils improved in the range of −10 to 34 points with the average pupil improving by 11 points. It can be seen that the data exhibits a marked degree of variation, which is good for the analysis of possible influencing factors.

**Table 1**
E—H—P factors model.

| Design principles | Design parameters | | Indicators | | Factors | | Classroom characteristics making up high ratings |
|---|---|---|---|---|---|---|---|
| Naturalness | N1 | Light | A | The quality and quantity of natural light the classroom can receive. | 1 | Orientation of the room facing | Daylight can penetrate into the room from more than one orientation and the south side is towards the sun's path for most of the year |
| | | | | | 2 | Glazing area/floor area | The classroom can receive more daylight if the ratio is higher. |
| | | | | | 3 | The most distant point from the glazing | The distribution of daylight level can be more even when this value is smaller. |
| | | | B | The degree to which the lighting level can be controlled manually | 4 | Quality of the electrical lighting | More electrical lighting with higher quality can provide better visual environment. |
| | | | | | 5 | Shading covering control | The blinds (shading coverings) are better than the curtains; All binds (shading coverings) are in good condition; The space adjacent to the window is clear. |
| | N2 | Sound | C | The frequency of the noise source's disturbance | 6 | Noise from the school outside | The room is far away from the road traffic and there is a buffer zone between the room and traffic road. |
| | | | | | 7 | Noise from the school inside | The windows are towards the quite area; There is no busy activity area adjacent to the room; The chairs have rubber feet. |
| | | | D | The degree to which the pupils can hear clearly what the teachers say | 8 | Size and shape (length/width) | It is easier for pupils to concentrate on teachers when the classroom is rectangular on plan rather than a square. |
| | | | | | 9 | Carpet area of the room | More carpet area is, less reverberation time (RT) can be. |
| | N3 | Temperature | E | The degree to which the pupil feel comfort in summer and winter. | 10 | Amount of the sun heat | Rooms with south façade can receive more sun heat than any other orientated rooms. |
| | | | F | The quality of the central heating system | 11 | Heating control | Underfloor heating is better when it comes to evenly distribute the heat with a thermostat. |
| | N4 | Air quality | G | The frequency of the contaminated air that comes into the classroom | 12 | Contaminated air inside the classroom | Usually, $CO_2$ level is lower if the room volume is bigger when same amount of people in it. |
| | | | | | 13 | Contaminated air from other spaces | The room is far away from the polluted air, e.g. toilet. |
| | | | H | The degree to which the stuffy feeling can be adjusted manually | 14 | Opening size | The air exchange is quicker when the opening size is bigger. |
| | | | | | 15 | Opening options | Different opening positions can give occupants more choices to increase the air movement. |
| Individualisation | I1 | Choice | I | The degree to which the distinct characteristics of the classroom allow the sense of ownership | 16 | "This is our classroom!" | Any design features that distinct characteristics of the room allow the sense of ownership. |
| | | | J | The degree to which the FFE are comfortable and familiar, supporting the learning and teaching | 17 | Furniture, Fixture and Equipment (FF&E) quality | The facilities are comfortable with high quality, supporting the learning activities. |
| | | | | | 18 | Quality of the chairs and desks | The desks and chairs are comfortable, interesting and ergonomic. |
| | I2 | Flexibility | K | The degree to which the pupils live together without crowding each other | 19 | Size for the pupil's activity area | Bigger size helps pupil to learn better. |
| | | | | | 20 | Configuration changed to fit the size of class | Easier the teacher change the space configuration, more teaching methods can be adapted to pupils learning. |
| | | | L | The degree to which the room plan allows varied learning methods and activities | 21 | Zones for varied learning activities | More zones can allow varied learning activities at the same time. |
| | | | | | 22 | Attractive (or useful) space attached to the classroom | The storage and/or breakout space are always available and not used for other purposes. |
| | I3 | Connection | M | The presence of wide and clear pathway and orienting objects with identifiable destinations | 23 | Corridor usage | It is not used for storage and/or breakout purpose. |
| | | | | | 24 | Corridor width | Wider the corridor is, quicker the movement can be. |
| | | | N | Clear and orienting corridor | 25 | Clear and orienting corridor | Large and visible pictures and or landmarks are along the pathway. |
| | | | | | 26 | Safe and quick access to the school facility | The room is near the main entrance and other specialist rooms, e.g. library, music, café etc. |
| Stimulation, appropriate level of | S1 | Complexity | O | The degree to which the school provide appropriate diversity (novelty) | 27 | Site area/total pupils in school | Bigger the site area is, more potential opportunities for the school to provide varied outdoor learning patterns and activities. |
| | | | | | 28 | Building area/total pupils in school | Bigger the building area is, more potential opportunities for the school to provide alternative learning rooms and spaces. |
| | | | P | | 29 | Diversity (novelty) | |

(*continued on next page*)

**Table 1** (*continued*)

| Design principles | Design parameters | Indicators | Factors | | Classroom characteristics making up high ratings |
|---|---|---|---|---|---|
| | | The degree to which the classroom provide appropriate diversity (novelty) | | | The interior decor can catch the pupils' attention and arousal, but in balance with a degree of order. Diversity and/or atypicality are expected to be good in producing stimulation. |
| | | | 30 | Quality of the display | The displays are stimulating, well designed and organized, ideally without cluttered noisy feelings. Diversity and/or atypicality are expected to be good in producing stimulation. |
| S2 | Colour | Q The degree to which the 'colour mood' appropriate for the learning and teaching | 31 | Colour of the classroom | Carefully considered colours for the wall and floor area. Taking age into consideration, warm colours may complement the young pupil's extroverted nature, while cool colours enhance the ability to concentrate on learning later. |
| | | | 32 | Colour of the furniture | Carefully considered colours for the furniture. Pupil age is also taken into consideration (same as 31). |
| | | | 33 | Colour of the display | Carefully considered colours for the display. Pupil age is also taken into consideration (same as 31). |
| S3 | Texture | R The degree to which the views of nature through the window | 34 | Distant view | There is a wide-field vision with sky, distant urban and rural area and landscape. |
| | | | 35 | Close view | There are full of natural elements, e.g. grass, garden, pond, tree etc. |
| | | S The presence of fabric variety, seasonal cycles and varied learning opportunities | 36 | Outdoor play quality | The pupils can have abundant play area outside, ideally adjacent to the classroom. |
| | | | 37 | Outdoor learning alternative | The pupils can have varied learning opportunities other than in the classroom. |

The outcome variable "pupil's learning progression", was calculated from the data supplied from Blackpool as follows.

- For each pupil the improvement in his or her reading, writing and math's TA levels over the year academic year 2010/2011 was calculated, i.e. end level minus the start level.
- These subject improvements were then added together for each pupil.
- Each improvement was then standardised by subtracting the average improvement across all pupils analysed and dividing this value by the standard deviation across all pupils analysed.

The data was careful assessed and pupils removed from the analysis for a variety of methodological reasons. One problem was that progress of pupils in the reception class is assessed differently to pupils in other years and the measures are not comparable. Also Blackpool council supplied these alternative measures as the start level for pupils in Year 1 for some schools. It was therefore decided to remove the reception classes and Year 1 classes where a pupil's start level was measured using this alternative scale. This meant seven reception and five Year 1 classes were excluded from the analysis (see Table 6); this led to 207 and 147 pupils being removed from the analysis, respectively. A further class was excluded because the start levels were not populated. In future work the issue of different performance measures will be re-examined and, at a minimum, a study will be carried out of the reception classes themselves.

Blackpool council was not able to supply start and end levels in each of the three subjects for some individual pupil's because they were not known, possibly owing to churn in the schools' populations. To calculate a pupil's learning progress all six values needed to be populated. This led to a further 283 pupils being excluded. This meant that overall 751 pupils were used in the modelling process, representing 53% of the original pupil data supplied by Blackpool Council.

Fifty percent of the pupils included were girls and 50% were boys. There was also a relatively even distribution in the month a pupil was born. The number of pupils used to develop the model was evenly spread across the sample schools. Generally, the school day is fixed, with a standard starting and finishing time. On average, all of these pupils are in their fixed classrooms to study and play, occupying 50–80% of the total school day. Thus, it is reasonable to think that the physical environment provided by their classroom could impact on the pupils' overall learning progress.

Using the data supplied from Blackpool council five non-environmental, or "pupil level", factors were created to control for the environmental factors as follows.

- Actual age: as supplied by Blackpool council.
- Month's age: as supplied by Blackpool council.
- Gender: as supplied by Blackpool council.
- Weighted start: this is a pupil's overall start level: To create a pupils overall start level a pupil's TA start level for reading, writing and math's were added together. This value was then standardised by subtracting the average start level across all pupils analysed (i.e. all 751 pupils) and dividing this value by the standard deviation across all pupils analysed.
- Weighted start on age: a pupil's overall start level depends heavily on his or her age. Therefore it was decided to calculate a factor which indicated whether a pupil's overall start level was above or below the average pupil of that age. To create this factor a pupil's TA start level for reading, writing and math's were added together. This value was then subtracted by the average start level for a pupil of the same age (calculated from the data) and this value was then divided by the standard deviation for a pupil of the same age (calculated from the data).

**Table 2**
Basic information about the investigated schools.

| | Year built | Site | Location | Site area ($m^2$) | Ground floor area ($m^2$) | Total floor area ($m^2$) | Total pupils | Age |
|---|---|---|---|---|---|---|---|---|
| School1 | 2002 | Open | Sub-urban | 15,621 | 2905 | 3059 | 451 | 3–11 |
| School2 | 1970s | Compact | Urban | 7244 | 1880 | 1880 | 79 | 2–19 |
| School3 | 1970s | Open | Sub-urban | 30,316 | 3346 | 3466 | 430 | 3–11 |
| School4 | 2000 | Compact | Sub-urban | 7229 | 3467 | 4407 | 442 | 3–11 |
| School5 | 1920 | Compact | Sub-urban | 7938 | 3039 | 4300 | 619 | 4–11 |
| School6 | 1902 | Compact | Urban | 7212 | 3412 | 5666 | 464 | 3–11 |
| School7 | 2006 | Compact | Urban | 9950 | 2237 | 5389 | 480 | 3–11 |
| School8 | 1900 | Compact | Urban | 1754 | 935 | 1130 | 211 | 4–11 |
| School9 | 1990 | Open | Sub-urban | 17751 | 1667 | 1667 | 143 | 3–11 |
| School10 | 1950s | Compact | Sub-urban | 858 | 183 | 366 | 12 | 4–15 |

It should be mentioned that to account explicitly for the effect of a teacher on a pupil's learning progression we investigated getting teachers' Ofsted ratings. However Blackpool council were only able to supply this information for two of the schools, so it was not used as a factor in the model at this stage. From the teacher data that we did receive for three schools, we do know that there was surprisingly little variation in the assessments given, perhaps indicating a quite consistent level of teaching within the national system in place. In addition we were able to isolate the scale of the teacher effect through the multi-level analytical approach described below.

### 3.3. Multi-level modelling strategy

The analytical strategy focused firstly on investigating the correlation between relevant factors and pupil's learning performance to give an initial impression of which factors may significantly impact on pupil performance. The main analysis employed a multi-level modelling approach [14] to determine the factors that significantly impact a pupil's learning performance. This was deemed to be the appropriate approach as it can reflect the "nested" structure of the data (pupil in class in school) so avoiding misleading results due to overestimation of significance.

This is achieved by providing a rigorous way of dealing with unmeasured "pupil effects", "class effects" and "school effects", by allowing the residuals to be partitioned at each level. Multi-level modelling is well tested in educational research, a specialist support Centre exists at Bristol University and this approach was used with success in Zeisel's study of built environment effects on Alzheimer's patients (A). A specialist off-the-shelf package was used to carry out the modelling [15]. In the event seven schools was found not to be sufficient to support multi-level analysis at the school level, however, this will be reassessed in future work when data from more schools is obtained.

**Table 3**
Descriptive statistics for the design parameters across 34 classrooms.

| Parameter | *N* | Minimum | Maximum | Mean | Standard deviation |
|---|---|---|---|---|---|
| Light | 34 | 2.20 | 4.23 | 3.3431 | 0.47804 |
| Sound | 34 | 2.08 | 4.38 | 3.4093 | 0.64096 |
| Temperature | 34 | 2.00 | 4.13 | 3.1949 | 0.69235 |
| Air quality | 34 | 2.22 | 4.56 | 3.3431 | 0.56927 |
| Naturalness | 34 | 1.75 | 4.63 | 3.3051 | 0.61483 |
| Choice | 34 | 1.13 | 3.88 | 2.4706 | 0.68469 |
| Flexibility | 34 | 1.50 | 4.31 | 2.8562 | 0.81128 |
| Connection | 34 | 2.50 | 4.50 | 3.2647 | 0.45202 |
| Complexity | 34 | 2.25 | 4.25 | 2.9779 | 0.52356 |
| Colour | 34 | 1.83 | 4.46 | 2.9449 | 0.69356 |
| Texture | 34 | 2.20 | 4.23 | 3.3431 | 0.47804 |
| Stimulation | 34 | 2.08 | 4.38 | 3.4093 | 0.64096 |

In more detail, the steps in the statistical analysis pursued were as follows.

Step 1
Calculate Pearson correlation [16] between a pupil's learning progress over the year and each of the 10 "design parameters", 37 "factors" and the four continuous non-environmental factors, namely weighted start level, weighted start level on age, actual age and months age. This gave an initial indication of which factors, at a significance level of 1%, affect a pupil's learning progress over the year.

Step 2
For the factor gender a 2 sample *t*-test [16] was calculated to see if the mean value for a pupil's learning progression over the year for girls was different to that for boys at a significance level of 1%.

Step 3
Calculate Pearson correlation between all environmental factors and continuous non-environmental factors. This was done to determine whether there is a potential for multicollinearity in the final model. Multicollinearity tends to be a problem if there are two factors in a model which produce a Pearson correlation of $>0.8$ or $<-0.8$.

**Table 4**
TA level to points conversion table.

| TA level | Points |
|---|---|
| P1i | 0.5 |
| P1ii | 0.7 |
| P2i | 0.9 |
| P2ii | 1.1 |
| P3i | 1.3 |
| P3ii | 1.5 |
| P4 | 2 |
| P5 | 3 |
| P6 | 4 |
| P7 | 5 |
| P8 | 6 |
| 1C | 7 |
| 1B | 9 |
| 1A | 11 |
| 2C | 13 |
| 2B | 15 |
| 2A | 17 |
| 3C | 19 |
| 3B | 21 |
| 3A | 23 |
| 4C | 25 |
| 4B | 27 |
| 4A | 29 |
| 5C | 31 |
| 5B | 33 |
| 5A | 35 |

**Table 5**
Descriptive statistics of the TA points pupils were awarded.

| Factor | Minimum | Maximum | Mean | Standard deviation |
|---|---|---|---|---|
| Start points (total) | 8 | 95 | 50.12 | 18.30 |
| End points (total) | 12 | 103 | 60.91 | 18.28 |
| Improvement points (total) | −10 | 34 | 10.78 | 5.62 |

Step 4

This step involved investigating whether a multi-level model is required. If there was no variation in a pupil's learning progression across classes and schools then this data can be analysed using a multiple linear regression model [17]. This was tested using two steps as follows.

(i) Test whether there is a variation across classes ($p < 0.05$ assuming one degree of freedom) by comparing the deviance for a two-level multi-level model that accounts for variation across classes with the deviance for the model that makes no account for variation across classes [18].

(ii) If no class variation was found then go to step 5, otherwise a test to see if there is variation between schools is conducted. The deviance for three level multi-level model which accounts for variation across schools and classes was compared to the deviance of the model obtained in (i).

Step 5

All non-environmental factors and hence all factors measured at the pupil level were tested and progressively entered into the model if they significantly affected a pupil's learning progression. This was tested using the following five steps.

(i) Each non-environmental factor was tested individually by creating a model, which entered this factor in the model and compared the deviance of this model to the deviance for the current model. The factor causing the greatest change in the deviance was entered into the model if the p-value for this change in deviance (assuming one degree of freedom) was less than 0.05.

(ii) If a non-environmental factor was entered into the model in (i) a test to see if the effect of this factor on a pupil's learning progression varies across the classes and schools was performed. If incorporating this into the model significantly changed the deviance then this was incorporated into the model ($p < 0.05$). It must be noted the change in deviance is assumed to follow the chi-square distribution with two degrees of freedom [18]. If a factor was not entered at (i) then go to Step 6.

(iii) Repeat (i) and (ii) for all non-environmental factors which were currently not in the model then go to iv.

(iv) If a non-environmental factor was not entered in the (iii) go to Step 6, otherwise each factor in the current model was tested to see if the removal of the factor caused the deviance to reduce significantly ($p < 0.10$).

(v) (iii) and (iv) were repeated until no more factors were entered.

**Table 6**
Number of classes and pupils excluded from the data supplied by Blackpool Council and the reason for excluding them.

| Exclusion reason | Number excluded | |
|---|---|---|
| | Classes | Pupils |
| Reception class | 7 | 207 |
| Alternative measure supplied as start level for Year 1 | 5 | 147 |
| Start levels not populated | 1 | 31 |
| Start and end levels not supplied for all 3 subjects | N/A | 283 |
| Total | 13 | 668 |

Step 6

All environmental factors (which are measured at the class level) were tested and entered into the model if they significantly affected a pupil's learning progression. This was tested using the following four steps:

(i) Each environmental factor was tested individually by creating a model that entered this factor in the model and comparing the deviance of this model to the deviance for the current model. The factor causing the greatest change in the deviance was entered into the model ($p < 0.05$ assuming one degree of freedom), otherwise no factors were entered into the model.

(ii) Repeat (i) for all environmental factors currently not in the model and then go to (iii).

(iii) If an environmental factor was entered into the model at ii, then each factor in the current model was tested to see if the removal of the factor caused the deviance to reduce significantly ($p < 0.10$), otherwise no more factors were entered into the model.

(iv) ii) and (iii) were repeated until no more factors could be entered.

## 4. Results

### 4.1. Initial bivariate analysis

Of the 10 environmental factors, eight displayed significant correlations with pupil's learning progression (weighted progress), but of these three were unexpectedly negative. This led to a reconsideration of the original hypothesised relationships in these areas. In the cases of "complexity" and "colour", this study's thinking was that these are parameters within the overarching design principle of "appropriate level of stimulation" and it would appear that for the task of learning, as reflected by SATs results, these scales should simply be reversed to reflect that "appropriateness" in this context means less, rather than more stimulation. This results in these correlations showing as positive in Table 7. In the case of "connection" the situation was again unexpected, but

**Table 7**
Pearson correlation between each factor and a pupil's learning progression.

| Factor type | Factor | | Weighted progress |
|---|---|---|---|
| Non-environmental | Weighted start | | −0.158** |
| | Weighted start on age | | −0.081* |
| | Actual age | | 0.019 |
| | Months age | | −0.087* |
| Environmental | Naturalness | Light | 0.177** |
| | | Sound | −0.083* |
| | | Temperature | 0.043 |
| | | Air quality | 0.120** |
| | Individualisation | Choice | 0.133** |
| | | Flexibility | 0.123** |
| | | Connection | −0.157** |
| | Stimulation | Complexity | 0.141** |
| | | Colour | 0.258** |
| | | Texture | 0.103** |

*Indicates significant factors at the 5% level; and ** indicates significant factors at the 1% level.

**Table 8**
Pearson correlation between all non-environmental factors.

| | Weight start level | Weighted start level on age | Actual age | Months age |
|---|---|---|---|---|
| Weight start level | 1.000 | | | |
| Weighted start level on age | 0.521* | 1.000 | | |
| Actual age | 0.851* | 0.044 | 1.000 | |
| Months age | 0.146* | 0.238* | 0.206* | 1.000 |

* Indicates significant factor at 1% level.

more complicated given some conflict in the performance correlations of the underpinning factors measured. So, in this case the scale was left as it was and the negative correlation is still evident in Table 7. Of the non-environmental factors, only a pupil's starting level was found to be significantly correlated with a pupil's learning progression, and this was negative too.

Tables 8 and 9 explore the issue of correlations between the various independent variables. Table 8 shows almost all non-environmental factors are significantly correlated with each other. In particular actual age is very highly correlated (value above 0.8) with a pupil's start level (weighted start level) suggesting there would be a multicollinearity problem if both terms were included in the final model. These two factors are expected to be highly correlated because a pupil's starting level improves with age.

Table 9 highlights that there are a lot of low-level correlations between the environmental factors, however they are not high enough to create a potential problem with multicollinearity. However because they are correlated it is likely that some of the environmental factors will not be entered into the final multi-level model because a factor that is correlated with it is already in the model.

### 4.2. Multi-level model

It was found that there was a significant variation in a pupil's learning progression between *classes*, however a significant variation in a pupil's learning progression between *schools* was not found. The reason for there being no significant variation in a pupil's learning progression between schools could be because only seven schools were used to create the model.

Therefore a two-level multi-level model was developed, as given in Table 8. This shows the factors that were found to significantly effect a pupil's learning progression, with all of these factors being standardised so the effect of each factor relative to the others can easily be determined. Six of these significant factors were environmental factors; namely colour, choice, connection, complexity, flexibility and light. Two non-environmental factors were found to significantly effect a pupil's learning progression; namely a pupil's weighted start level and a pupil's weighted start level relative to the average pupil of the same age.

The multi-level model (Table 10) displays the intercept variance, which for this model takes the value 0.102. The intercept variance is the variability in the class level (level 2) residual, where the class level residual represents the departure of the average pupil's learning progression in a classroom from the average pupil's learning progression over all pupils in the population. Therefore all pupils in a particular classroom will have the same value for the residual. The intercept variance gives the unexplained variation (or variation after adjusting for the class level factors) in a pupil's learning progression at the class level and quantifies the unexplained variation in a pupil's learning progression across classes.

Table 10 also shows the random error to be 0.523; this is the variability in the pupil level (level 1) residual, where the pupil level residual represents the departure of a pupil's improvement from the average improvement of a pupil in the classroom in which they study. Therefore all pupils will have a different value for this residual. The random error is the unexplained variation (or variation after adjusting for the pupil level factors) in a pupil's learning progression at pupil level.

The $R^2$ value gives an indication of the percentage of the variation in a pupil's learning progression that can be explained by all the factors in the model and it determines how well the model fitted the data [19]. The $R^2$ value was 51% therefore 51% of variation in pupil's learning progression can be explained by the environmental and non-environmental factors (incorporating unexplained differences between classes).

### 4.3. "Class level" E–H–P influences

Table 10 shows that six out of the 10 environmental factors were found to significantly affect a pupil's learning progression. The five environmental factors colour, choice, complexity, flexibility and light were found to have a positive effect on pupil's learning progression. However, as indicated in the bivariate analysis above, the environment factor "connection" was found to have a negative effect on a pupil's learning progression (hence the parameter estimate in Table 10 is negative), thus it would seem that an increase in this environmental factor will lead to a decrease in a pupil's learning progression. It is clear that this factor is important with respect to learning, but the mechanism is not fully understood at present and will be a focus for consideration in future works.

The parameter estimates shown in Table 10 determine how influential a factor is on a pupil's learning progression. The larger the value (regardless of sign) the more effective the factor. Thus, the relative influence of the environmental factors is given in Table 11.

The class level (level 2) "proportion reduction variance" (PRV) can be used to investigate how the environmental factors account for variability among the classes. The class level PRV is how much

**Table 9**
Pearson correlation between all environmental factors.

| | Light | Sound | Temperature | Air quality | Choice | Flexibility | Connection | Complexity | Colour | Texture |
|---|---|---|---|---|---|---|---|---|---|---|
| Light | 1.000 | | | | | | | | | |
| Sound | 0.438* | 1.000 | | | | | | | | |
| Temperature | 0.182* | 0.043 | 1.000 | | | | | | | |
| Air quality | −0.179* | −0.487* | −0.150* | 1.000 | | | | | | |
| Choice | 0.259* | 0.098* | −0.056 | −0.138 | 1.000 | | | | | |
| Flexibility | −0.079 | 0.102* | −0.020 | 0.111* | 0.352* | 1.000 | | | | |
| Connection | 0.065 | 0.060 | 0.058 | 0.023 | 0.080 | 0.341* | 1.000 | | | |
| Complexity | 0.239* | −0.379* | 0.182 | 0.386* | −0.130* | −0.045 | 0.223* | 1.000 | | |
| Colour | 0.152* | −0.188* | −0.400 | 0.033 | −0.068 | −0.048 | −0.041 | 0.046 | 1.000 | |
| Texture | 0.163* | −0.093 | −0.790 | −0.088 | −0.088 | 0.039 | −0.117* | −0.299* | 0.444* | 1.000 |

* Indicates significant factors at 1% level.

**Table 10**
The parameter estimates and corresponding standard errors for the multilevel model.

| Factor | Parameter estimate | Standard error |
|---|---|---|
| Intercept | 0.006 | 0.064 |
| Weighted start | −0.202 | 0.078 |
| Weighted start on age | −0.018 | 0.098 |
| Colour | 0.199 | 0.065 |
| Choice | 0.11 | 0.069 |
| Connection | −0.289 | 0.067 |
| Complexity | 0.191 | 0.067 |
| Flexibility | 0.196 | 0.07 |
| Light | 0.138 | 0.067 |
| Intercept variance | 0.102 | 0.033 |
| Weighted start on age variance | 0.206 | 0.06 |
| Covariance between the intercept and weighted start age | −0.06 | 0.033 |
| Random error | 0.523 | 0.028 |

the intercept variance was reduced by adding the environmental factors [19]. Therefore the PRV value gives an indication of much of the variability among the classes is explained by environmental factors. Table 12 shows the intercept variance for the model with just the non-environmental pupil level factors in was 0.384, this reduced to 0.102 when the environmental factors were added to the model. Therefore the proportion reduction in the intercept variance by adding the environmental factors to the model is (0.384−0.102)/0.384 = 73%.

### 4.4. “Pupil level” influences

Table 10 shows the non-environmental (or pupil level) factors (“weighted start” and “weighted start on age”) significantly affect a pupil’s learning progression. These are both measured at the pupil level. Weighted start has a negative effect on pupil’s learning progression, which means that as a pupil’s starting level increases the pupil’s learning progression decreases. Hence the higher the starting level the less a pupil will progress.

The effect of “weighted start on age” on a pupil’s learning progression was found to be different for each class. “Weighted start on age” is the starting level of a pupil relative to the average pupil of the same age. Table 10 shows the variability in the residuals of the effect of “weighted start on age” (0.206). The residual represents the departure of the effect of “weighted start on age” on a pupil’s learning progression in a classroom from the average effect of weighted start on age on a pupil’s learning progression over the population, and so each classroom will have a different residual.

The residuals for the effect of “weighted start on age” were negative for every Class 6. This indicates that a pupil in Class 6 with a high starting level (compared to the average pupil of the same age) improved less. This is possibly because this is the last year of primary school and pupils with a high start level may not be able to achieve a higher level over the year as they had reached the highest possible level that can be achieved already at the beginning of the year. This will be investigated further in the future.

**Table 11**
The proportion of increase in a pupil’s learning progression accounted for by each of the environmental factors.

| Environmental factor | Proportion (%) |
|---|---|
| Colour | 18 |
| Choice | 10 |
| Connection | 26 |
| Complexity | 17 |
| Flexibility | 17 |
| Light | 12 |
| Total | 100 |

**Table 12**
Proportion reduction in variance (PRV) by adding level 1 and level 2 factors to the model.

| Model | Random error | Intercept variance |
|---|---|---|
| No factors in model | 0.695 | 0.347 |
| Pupil factors only | 0.524 | 0.384 |
| Both pupil factors and environmental factors | 0.523 | 0.102 |
| *PRV* | | |
| Level 1 | 25% | |
| Level 2 | | 73% |

The pupil level (level 1) “proportion reduction variance” (PRV) can be used to investigate variability at the pupil level. PRV, in this case, is how much the random error (see Table 12) reduced by adding the non-environmental factors to the model [19]. This gives an indication of how much of the pupil level variation is explained by the non-environmental factors (all measured at the pupil level). It can be seen from Table 12 that the random error for the model with no factors in was 0.695, this reduced to 0.524 when the non-environmental factors were added to the model. Therefore the proportion reduction in the random error by adding the non-environmental factors to the model is (0.695−0.524)/0.695 = 25%.

## 5. Discussion

### 5.1. The model

As set out above, the main analysis employed a multi-level modelling approach as this can reflect the “nested” structure of the data (pupil in class). This enables the unmeasured “pupil effects” and “class effects” to be partitioned as residuals at each level, so avoiding misleading results owing to the overestimation of significance that a simple regression analysis would deliver.

Overall the model explains 51% of the variability in the learning improvements of 751 pupils, over the course of a year in 34 classrooms, across seven schools. The reduction in the random error at Level 1 (*pupil* factors) is 25%, leaving a high unexplained variation (or random error), which could be due to factors such as a pupil having difficulties at home, a pupil being unwell or developing behaviour problems, or possibly a pupil gaining extra tuition. This kind of information would be difficult to collect. Also every pupil, as an individual, develops differently, which can never be fully explained by a model.

In contrast, the reduction in variance at Level 2 (*class* factors) is 73%, linked entirely to the six design parameters in the model. Thus, only a relatively small random error remains at this level. As this level of analysis is the focus of this study, the high level of explanation attached to the environmental factors is very important.

The relatively small unexplained variability is probably mostly due to measures of the teachers’ effectiveness not being directly represented in the model. As mentioned above, this aspect will be important, but may not vary very greatly in practice, however, its omission could introduce some bias in the parameter estimates and therefore some bias in how effective each factor is on a pupil’s learning progression. This would be more of a problem if a strong relationship could be anticipated between the teacher effect and the factors in the current model. Teachers of course make decisions about the arrangement of the physical classroom environment, but these are still environmental factors. For the other aspects of teacher effectiveness the connection to environmental factors, and so the bias, is probably only small and the current model can be seen to give a good initial indication of the effectiveness of current factors.

Six of the 10 built environment “design parameters” were identified as being particularly influential in the multi-level linear regression model. Taken together these have been shown to significantly influence pupil progression and to account for a large part of the variability in pupil performance at the class level. The six parameters are colour, choice, connection, complexity, flexibility and light.

All of the other environmental factors were found to be individually significant, but are not in the model mainly because, with this dataset, they are quite extensively correlated with other design parameters (see Table 9 above), albeit at a low level. The effect of this is that these factors were “competed out” of the regression analysis. At a practical level it could be that certain factors are less evident because they vary little between the classes in this sample. This would seem to apply air quality, which based on $CO_2$ spot checks in the classrooms, was found to be almost universally *poor*, confirming Clements-Croome et al.’s [20] detailed longitudinal observations in classrooms. Another possible issue is where a factor is so important that it is not allowed to get too bad. Huang et al. [2] term this as having “one vote veto power” (pp. 307–308), that is, if such a factor is at an unacceptable level the overall environmental quality will be judged as poor irrespective of how good other factors are. Huang et al found in a study of offices that this applies to high levels of sound and either extreme of temperature. So it could be that the “natural” factors of air quality, temperature and sound are important but did not rise to the top of the analysis as they are either, generally, but imperceptibly poor, or conversely they simply have to be addressed by users and so are not allowed to get very poor in practice.

That said the six factors identified have been shown significantly to influence pupil progression in practice. It could be that with more data and future analyses different factors could come to prominence, but this does not belie the strength of the overall correlations found or the importance of the factors identified here. It is interesting to see (Table 9) that there is a relatively even spread of influence across all six factors. This resonates with Huang et al.’s [2] observation that: “Physical environmental parameters are all interrelated and the feeling of comfort is a composite state involving an occupant’s sensations of all these factors” (p. 305). Or as Cabanac [21] puts it “subjects tended to maximise the algebraic sum of their sensory pleasures” (p. 8).

The above statistical analysis has established a robust multilevel model of the factors that correlate with improvements in pupil performance. The following section takes this model and carries out further a further analysis to forecast the scale of the impacts implied in the model as it stands.

### 5.2. Implied learning impacts of the E–H–P factors in the model

The $R^2$ value was used to quantify the variance in a pupil’s learning progression explained by the environmental and non-environmental factors (incorporating unexplained difference between classes), which is 51%. The $R^2$ value cannot, however, be used to quantify the variability in a pupil’s learning progression explained by only the non-environmental or environmental factors, respectively, as each sub-analysis will be biased by the omission of the other factors.

However, we have established that the model has a good fit with the data, especially at the “class” level, where our principal investigative interest lies. Thus, the following analysis quantifies the impact of the environmental factors using the model in a forecasting sense. Highlighting differences in a pupil’s learning progression between the best and worst classes, owing to the environmental factors.

By fixing all the variables, except for the environmental factors, to their average values the model could be used to predict the weighted progress (pupil’s learning progression), owing to the environmental factors only. This in effect took an average pupil with an average teacher (represented by fixing the unexplained variation at class level) and placed them in each of the thirty-two classrooms studied (see Table 13).

Thus, this “average pupil” in the worst class had a predicted weighted progress of −0.82, which equates to an improvement of 6.15 points across the three subjects (see Table 4). However, placing this “average pupil” in the best class would result in a weighted progress value of 1.1, which equates to an improvement of 16.98 points across the three subjects. Therefore, by taking the difference between these values, the environmental factors alone can be seen to have an impact on a pupil’s learning progression of up to 11 points (16.98−6.15), summed across all three subjects. This suggests that placing the same pupil in the “best” rather than the “worst” classroom would have an impact on their learning that equates to the typical progress of a pupil over one year (11 points – see Table 5).

In the dataset considered here, the best and worst pupils improved by 34 and −10 points, respectively, across the three subjects over the year (see Table 5). This enables the impact of the environmental factors on learning progression to be scaled at 25% ($(11/44) \times 100$) along the range of values improvement takes (in the current dataset).

**Table 13**
Predicted weighted progress and the corresponding improvement points by class. (Improvement points are the sum of the improvement in points over the year for the three subjects).

| School | Class | Weighted progress | Improvement points |
|---|---|---|---|
| 8 | 3 | −0.82 | 6.15 |
| 8 | 5 | −0.73 | 6.69 |
| 3 | 5 | −0.57 | 7.56 |
| 6 | 4 | −0.40 | 8.51 |
| 7 | 3 | −0.40 | 8.56 |
| 6 | 3 | −0.35 | 8.84 |
| 8 | 4 | −0.34 | 8.88 |
| 3 | 4 | −0.26 | 9.34 |
| 3 | 3 | −0.24 | 9.42 |
| 4 | 4 | −0.17 | 9.84 |
| 4 | 5 | −0.15 | 9.96 |
| 4 | 3 | −0.12 | 10.13 |
| 4 | 2 | −0.08 | 10.35 |
| 6 | 5 | −0.07 | 10.37 |
| 9 | 4 | −0.06 | 10.43 |
| 5 | 1 | −0.03 | 10.61 |
| 5 | 3 | −0.02 | 10.70 |
| 7 | 4 | −0.01 | 10.71 |
| 9 | 3 | 0.03 | 10.94 |
| 7 | 6 | 0.04 | 11.02 |
| 3 | 2 | 0.05 | 11.05 |
| 8 | 6 | 0.07 | 11.18 |
| 5 | 6 | 0.08 | 11.23 |
| 7 | 5 | 0.22 | 12.05 |
| 5 | 4 | 0.23 | 12.09 |
| 6 | 2 | 0.31 | 12.52 |
| 6 | 6 | 0.33 | 12.66 |
| 9 | 2 | 0.38 | 12.94 |
| 6 | 1 | 0.48 | 13.46 |
| 7 | 2 | 0.61 | 14.21 |
| 5 | 5 | 0.66 | 14.49 |
| 5 | 2 | 0.86 | 15.60 |
| 4 | 6 | 0.88 | 15.72 |
| 9 | 5 | 1.10 | 16.98 |

**Table 14**
The most distinctive classroom characteristics that relate to the improvement of the pupils' academic achievement via the model.

| Design principle | Design parameter | Good classroom features | |
|---|---|---|---|
| Naturalness | Light | ◆ | Classroom receives natural light from more than one orientation. And (or) natural light can penetrate into the south windows. |
| | | ◆ | Classroom has high quality and quantity of the electrical lightings. |
| | | ■ | The space adjacent to the window is clear without obstruction. |
| Individualisation | Choice | ◆ | Classroom has a high-quality and purpose-designed Furniture Fixture & Equipment (FF&E) |
| | | ◆ | Interesting (shape and colour) and ergonomic tables and chairs. |
| | Flexibility | ◆ ■ | More zones can allow varied learning activities at the same time. |
| | | ◆ ■ | The teacher can easily change the space configuration. |
| | Connection | ◆ | Wide corridor can ease the movement. |
| | | ■ ▭ | The pathway has clear way-finding characteristics. |
| Stimulation, appropriate level of | Complexity | ◆ | Big building area can provide diverse opportunities for alternative learning activities. |
| | | ■ | With regard to the display and decoration, classroom needs to be designed with a quiet visual environment, balanced with a certain level of complexity. |
| | Colour | ■ | Warm colour is welcomed in senior grade's classrooms while cool colour in junior grades, as long as it is bright. |
| | | ■ ◆ | Colour of the wall, carpet, furniture and display can all contribute to the colour scheme of a classroom. However, it is the room colour (wall and floor) that plays the most important role. |

◆: design-related classroom features; ■: usage-related classroom features; and ▭: future study is needed to pursue its positive characteristics.

## 6. Conclusion

### 6.1. Generally

A range of hypotheses was tested using data on 751 pupils from 34 classrooms in seven schools. Clear impacts on learning progression by a range of environmental design parameters have been identified, using multi-level statistical analysis. Up until this point the parameters have been listed in the order in which the analysis produced them. Now they are summarised in Table 14, using the structure of Table 1, so that the relationship to the over-arching design principles can be seen.

It should be remembered that the spaces have been assessed in functional terms, focusing entirely on the impact of the differences between spaces on the academic performance of the pupils. In this context it can be seen that parameters to do with the design principle of "individualisation" are prominent. Here the issue of connection has raised some surprising issues compared with prevalent theory, but these can be seen to make sense if a pupil's perspective is taken. Achieving the "appropriate level of stimulation" for learning is also important and raises the issue of functional requirements versus aesthetic preferences. So young children may like exciting spaces, but to learn it would seem they need relatively ordered spaces, but with a reasonable degree of interest. In the area of "naturalness", only the parameter of light remained in the equation, and even this was quite a complex relationship between a desire for light, a dislike of glare and the importance of good artificial lighting. The other parameters for naturalness did not show up so strongly, and possible reasons for this are discussed above.

In Table 14 the features of "good" classrooms are distinguished as being either primarily design-related or use-related (or both). There is quite an even mix indicating that both designers and users have significant opportunities to take these findings into account in the design of their classroom spaces.

### 6.2. Limitations and future research

The study to date has involved a limited number of pupils in a particular area, with a focus solely on their academic performance. Clearly more work is needed. This study has provided important insights into the combined impacts of built environment factors on the learning progress of pupils. In the process it has also challenged the research team in various respects and much has been learnt that can be factored into future studies. In particular:

(a) The work will be extended to additional schools in other geographical areas in order to test, validate and illustrate the results to date. This will involve a replication of the existing methodology, enhanced through experience to date, plus additional dimensions, such as targeted classroom observations. In doing this further work:
  (i) The possibility of revealing "school" level effects will be revisited.
  (ii) Redoubled efforts will be made to gain access to measures of teacher performance, so that this aspect can be more clearly isolated in the analysis.
  (iii) The issue of "connection" will be explored further.
  (iv) The four aspects that were competed out of analysis at this stage (sound, temperature, air quality and texture) will be retained and explored further in the context of a larger and more varied sample.

(b) In the future, options to extend the work to other building use types will be considered, as will cross-cultural comparisons.

### 6.3. A significant direction

Given the size of the challenge as indicated in Section 1, it is a significant step that a hypothesis-led, multi-level model that explains 51% of the variation in pupil learning has been successfully developed. All the more so as it reveals that the six identified E–H–P design parameters account for a 73% reduction in unexplained variance at the class level. The impact of these environmental factors alone has also been scaled and appears to account for, in the order of, 25% of the learning progression of pupils.

We anticipate that this team and others will be able to fruitfully build on the direction we have set out upon in this study, both in relation to schools and for other use types.

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EPSRC has funded the HEAD project (grant ref EP/J015709/1) and this is the vehicle through which this body of work has been brought to this point and will be taken forward over the next 18 months to explore further the questions this initial work has raised.

Without all of this support this project would not have been possible and, as the project team, we would like to take this opportunity to express our appreciation for it.

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