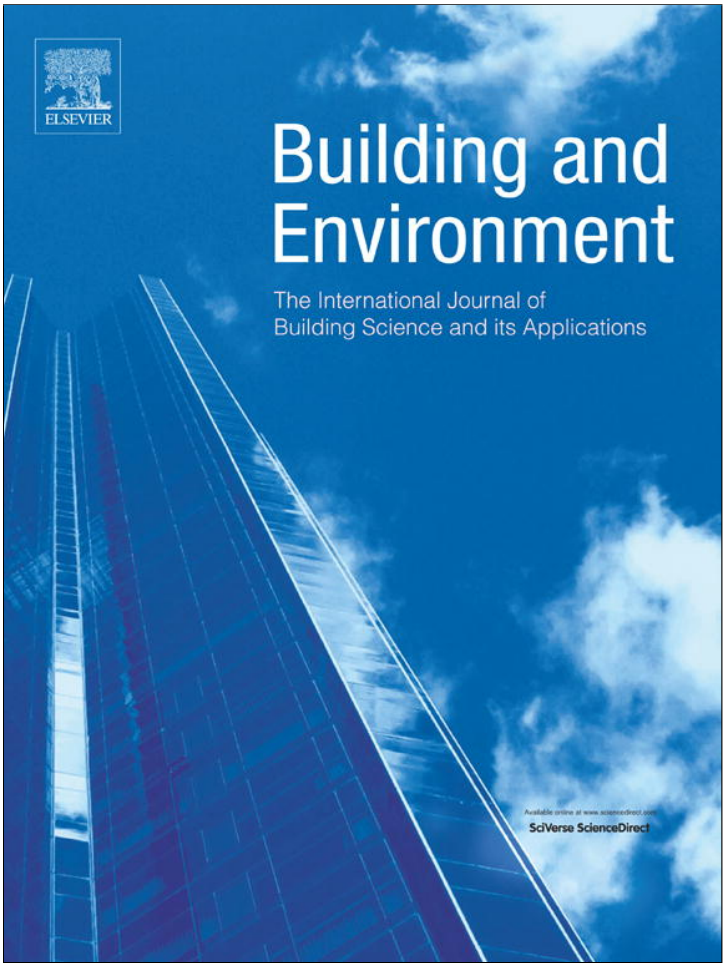
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Achieving a step change in the optimal sensory design of buildings for users at all life-stages

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A B S T R A C T

A general gap in knowledge around the holistic impact of spaces on human performance is identified. It is argued that filling this gap demands that the conceptual and methodological complexity of real world users' experiences of built spaces is addressed. It is argued that a potentially productive way forward is to use multi-level modelling within a neuroscience-informed, holistic sensory approach. Published results are highlighted in support of this approach, focused particularly on primary schools.

The potential of expanding this approach to a full range of life-stages is then explored, building on a view of the brain as it evolves across the human life-span. The separation of left/right-brain cognitive processes emerges as being potentially important as an intervening variable. The schools' data is re-analysed by subject using multi-level modelling to provide, maybe for the first time, proof of concept evidence of variations in the optimal space characteristics depending on brain lateralisation.

In addition significant differences are identified in the particular types of spaces involved and the relevant measures of human performance. These range from: classrooms and learning for school pupils; to offices and productivity for workers; to housing and well-being for the elderly.

The train of argument is brought together around a vision for the development of a general model for holistic sensory space design. This would address a number of life-stages and, through a progressive meta-analysis, it is suggested that, over time, an evidenced, whole-life perspective on the holistic impact of spaces on human performance can be achieved.

1. Introduction/structure of paper

It has been estimated that people spend 90% of their entire lifetime within buildings [1–3]. Furthermore, around 5.75% of GDP in developed countries is spent on construction activity to create or improve the built environment [4]. Yet there is no real understanding of the *holistic* impacts of built spaces on human functioning, despite huge amounts of information on individual aspects, such as heat and light [5]. The potential to enhance people's well-being and effectiveness would be huge if a clearer understanding of the overall impact of spaces could be achieved. Equally the built environment sector could orientate its efforts more effectively to support building users and, in so doing, would actively address the core social and economic dimensions of sustainability.

The thrust of this paper is as follows:

- Section 2 highlights the importance of the users' perspective and the research challenge around holistic impacts is brought into focus.
- Section 3 sets out how the complexity of the research challenge can possibly be addressed, conceptually and methodologically. This is illustrated by reference to a published study that successfully utilised the approach advocated, applied to primary schools and pupils' learning rates.
- Section 4 uses a whole-life model of the development/decline of the human brain, to explore how the above approach could be extended to a number of life-stages, namely: secondary school pupils, the working population and older people. The potential role of left/right-brain activity as an intervening variable emerges from this discussion.
- Section 5 provides clear proof of concept, from a reanalysis of the primary school data, that optimal built environment conditions *do* vary depending on brain function lateralisation.
- Section 6 returns to the three life-stages covered in Section 4 and clarifies that, in each case, there is a research gap in terms of the holistic impact of spaces on users, but that the spaces and human performance measures vary in each case: classrooms and learning for school pupils; offices and productivity for workers; and housing and well-being for the elderly.
- Section 7 brings together the previous sections into a vision for the development of a general sensory space design theory,

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involving focused studies in each of the areas and meta-analysis across the studies.

- Section 8 summarises and concludes.

2. Context

2.1. Strands of development

Internal environment quality (IEQ) research has primarily focused on the readily measurable aspects of: heat, light, sound and air quality, and although impressive individual sense impacts have been identified, it has been a struggle to explain variations in overall human performance with these variables. Indeed Kim and de Dear [6] argue strongly that there is currently no consensus as to the relative importance of IEQ factors for overall satisfaction.

In parallel, a literature and area of practice has developed around "building performance" with a wide variety of typologies on offer [7,8]. The intelligence gained should feed forward into new designs, however, post-occupancy evaluations (POEs) are not commonplace and the lessons learnt are not generally available for use in practice [9]. The concept of Building Performance Evaluation (BPE) argues for the deployment of user performance data throughout the whole-life-cycle of the building. In a recent benchmark for BPE [10] it is made clear that BPE aspires to objectivity using *"actual performance of buildings [assessed through] established performance criteria … objective, quantifiable and measurable 'hard' data, as opposed to soft criteria … qualitative … subjective"* (p. 27–28). However, in practice this is difficult and hardly anywhere amongst the collected chapters is such evidence actually delivered, with the most common approach being occupant surveys with occasional interviews (p. 169).

Another strand of development in recent years has been the rise in polemical works arguing for "inside-out design" [11] that builds from a focus on user needs and challenges the visual dominance of much design effort [12]. This is twinned by those arguing specifically for aspects of sensory-sensitive design [13,14]. Whilst Mallgrave [15] takes in a broad historical sweep and calls for the "'reassertion of the human body as the locus of experience' (quoting Holl et al. [16]) … [that has] been shunted aside by high-minded abstractions and abject formalism." (p. 205).

2.2. The emerging challenge

These complementary efforts stress that the evidence of building users' needs should be taken more fully into account and provide copious case study examples of potential *elements* of "good" design solutions. However, there remains a big gap between these putative elements and effectively achieving the desired *holistic* effects for users. Some specific aspects linked to "real" impacts have gained traction, for example Ulrich's [17] classic evidence of the positive healing effects of views of nature. There has been progress from this promising start, for example around individual control of thermal conditions in hospitals [18], but this still falls a long way short of comprehensively addressing the complexity of the design challenge. The difficulty of studying multiple dimensions is illustrated by the problems encountered when the impressive Heschong Mahone [19,20] daylighting studies extended to include other issues. It is also evident in Tanner's [21] struggle to analyse the multiple aspects impacting on learning rates in schools.

So there exists an important research challenge around the issue of better understanding, and evidencing, the holistic impacts of spaces on users.

3. Addressing the challenge

This research challenge has two dimensions. First, a way has to be found to address the *conceptual* complexity of the real world factors to be considered (and the wealth of state-of-the-art knowledge, from a range of disciplines). Secondly, the *practical* complexity of the analysis needs to be addressed.

3.1. Addressing the conceptual complexity

An over-arching conceptual perspective is essential to synthesise the alternative design factors into a form that can generate hypotheses for optimal design, which can be tested. An interesting possible way forward is to use the simple notion that the effect of the built environment on users is experienced via multiple sensory inputs in particular spaces, which are resolved in the users' brains. These mental mechanisms can provide a basis for understanding the combined effects of sensory inputs on users of buildings at a level of resolution where "emergent properties" [22] may be evident. This is the approach being promoted by the Academy of Neuroscience for Architecture (ANFA), based in San Diego, and stimulated by, eg Eberhard's [23] work. Arbib [24] makes an interesting distinction between, what he terms "neuromorphic architecture" and Eberhard's "neuroscience of the architectural experience". In simple terms, the former addresses analogies of brain functioning for designed spaces and the latter the impact of spaces on the brain.

The approach taken here is neither of these and is not concerned with the brain per se. Rather it employs the broad characteristics of brain functioning to structure the sensory factors to be considered with a view to better understanding the holistic impacts of spaces on human performance and well-being [25]. It could be said to focus on neuro-informed architecture. Until recently the only exemplar study using this sort of thinking was focused on Alzheimer's care facilities [26], which successfully demonstrated how characteristics of the built environment, viewed through a neuroscience lens, can have medically convincing impacts on symptoms such as aggression and depression.

The implication is that the structuring of the brain's functioning can be used to drive the selection and organisation of the environmental factors to be considered, not just their inherent measurability. This approach to postulating "generative mechanisms" underlying the complexity observed, has been termed "retroduction" [27]. Thus, drawing especially from Roll's [28] detailed description of the brain's implicit systems, a novel organising model has been proposed [25]. This structures the factors to be considered into:

- Naturalness: eg, light, sound, temperature and air quality.
- Individualisation: eg, choice, flexibility and connection.
- Appropriate level of stimulation: eg, complexity, colour and texture.

The rationale for the choice of these themes [28] can be summarised as follows. First, as our emotional systems have evolved over the millennia in response to our natural environment, it does not seem unreasonable to suggest that our comfort is likely to be rooted in key dimensions of 'naturalness'. This is encoded via the action of hard-wired 'primary reinforcers' operating in the orbito-frontal cortex of our brain where the value of the environmental stimulus is assessed. Examples would be our attraction towards fresh air and daylight. Second, over time individuals build connections between 'primary reinforcers' and complex representations of 'secondary reinforcers'. Taken together with the situated nature of memory, these personal value profiles lead to highly individual responses to space, leading to the potential importance of 'individualization' as an additional, key, underlying design principle. Examples would be associations, say between particular smells and colours, and positive (or negative) events in our lives. Third, lying behind the above there is a recurrent theme around the general level of stimulation that is appropriate for given situations, eg, sleep versus a learning situation.

Within this structure the full range of relevant factors (e.g. light, layout, etc.) that might be elements of "good" design for a particular scenario (school, work, etc.) can be grouped so providing a clear and balanced set of hypotheses to be tested.

3.2. Addressing the practical analytical complexity

The second aspect concerns the analysis of complex data. As the focus is on people in spaces it is inherently nested (e.g. pupil in class in school). This suggests the potential value of multi-level modelling, which is well tested in educational research [29,30] and was used with success in Zeisel et al.'s study of built environment effects on Alzheimer's patients, mentioned above. Multi-level modelling has technical advantages in that it avoids misleading results due to the overestimation of significance by providing a rigorous way of dealing with unmeasured effects by allowing the residuals to be partitioned, or separated out, at each level [31,32]. For the sort of research challenge being addressed here there is another big advantage and this is that the variability in a chosen dependent variable linked to the individual level (eg pupils, with their potential for huge variations) can be isolated from the variability associated with the space level (eg class). This opens up the possibility that, even though a high level of explanation may not be possible at the individual level, it can be partitioned off as an identified component of the unexplained variability, thus enabling the effects at the space level to be modelled separately, but still in an holistic context.

3.3. Initial proof of concept

Using these two approaches together to address the issue of holistic built environment effects on humans, in spaces, appears to be a potentially fruitful way forward. However, the utility of this approach depends, of course, on whether it allows clearer insights to be derived through practical research. A pilot project on primary schools has been carried out using this approach. The published results of this have provided strong support for the efficacy of this approach to addressing both the conceptual and practical complexity inherent in "natural" data of the sort studied [33]. At the "class" level, 73% of the variation in learning rates of 751 pupils, based on their test results, was explained by six built environment design parameters, which together make up an estimated 25% of the overall influences on learning rates. This appears to be the first time this impact has been successfully isolated and clearly evidenced.

Based on the experience of this focused study of primary schools in the UK, it seems evident that the approach to the research challenge, set out above, does have the potential to reveal the holistic impacts of spaces on people, and furthermore, these impacts are potentially very large. Clearly, if these effects can be more fully understood for all users of spaces there is tremendous potential to improve peoples' lives and make optimal use of the huge investments being made in the built environment.

4. Optimal sensory design of buildings across life-stages

It is suggested that the proof of concept work outlined above, provides the initial traction necessary to consider it feasible to create a general model, and clear measures for, a neuroscience-informed, sensory design approach to the built environment. This has the potential to deliver a complex understanding of the impact the built environment has on human development and well-being, covering a comprehensive range of life-stages and activities.

4.1. Developing a neuroscience-informed whole-life view

Key to this is scaling-up of the application of the ideas presented, is to consider how the human brain varies in its characteristics over a lifetime. Two fairly extreme life-stages are already in place via the studies of optimal sensory spaces for both primary school children [33] and for the optimal care of Alzheimer's patients [26].

But what happens in between the rapid development of the young brain and the eventual deterioration of the old brain? Desjardins and Warnke [34] synthesise multiple studies of the variation of cognitive skills across the human life-span and indicate that "fluid" brain activity (reflecting perceptual speed, reasoning, spatial ability) will typically have peaked around the age of twenty and declined from there on. In contrast, "crystallised" intelligence (pertaining to factual general or vocabulary knowledge) may well increase and endure, reflected in the sustained verbal capacity of many of the elderly. The typical outcome seems to be that capability against traditional intelligence scores grows rapidly up to around twenty years' of age and then flattens out for many decades thereafter, however, the character of the thinking taking place changes (see Fig. 1).

4.2. The emergence of the possible importance of left/right-brain functioning

It can be seen that there could be a parallel between the ageing brain and the balance of left-brain (eg analytical-logical-verbal) and right-brain (eg, sensory-emotional-holistic-spatial) functioning [35]. Indeed, this appears to be the case with a tendency towards left-brain domination as individuals age, finessed by an apparent compensatory functional shift away from the clear left-right lateralisation normal in younger brains [36].

This emerging overlay of left/right-brain activity raises the question as to whether this is an issue at other life-stages. In schools the lines are not cleanly drawn by subject, but grammar and reading do appear to be mainly left-brain activities, whereas mathematics is more mixed [37]. So it would seem that subject-specific brain functioning for school pupils may be an issue and any environmental insights from this context could, additionally,

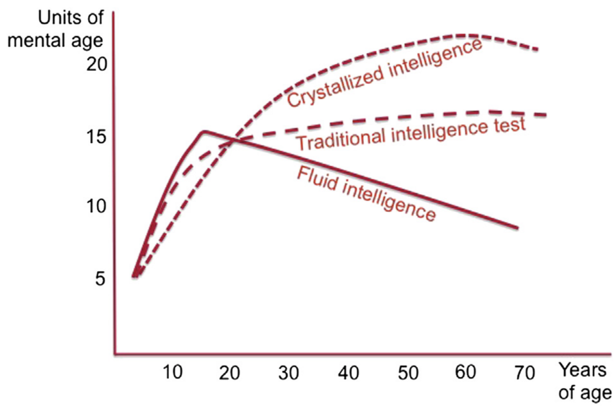

Fig. 1. The ageing brain (Desjardins and Warnke, 2012, p. 9).

hold clues for appropriate environments for the (typically) lateralised brain functioning of the elderly.

Then there is the question of the working population between these two life-stages, around 46% of whom it can be estimated work in office situations [38]. Here age and task interact to create a cocktail of factors. Responding to the needs of up to four generations in the work place has been highlighted as a complex and growing issue [39], and provides an interesting dynamic that connects the perspectives around schools and older people into a whole-life perspective. However, design for productivity amongst an increasingly multi-generational workforce, also needs to take into account both relatively standardised tasks (tending to the logical, precise left-brain) and creative activities (engaging the emotional, holistic right-brain too). Although much office work is fairly procedural, as Hodulak [40] observes: "increasingly innovation is a decisive competitive factor" (p. 98). Innovation can be taken as the operationalised form of creativity, where new ideas are taken through to implementations that benefit the organisation in question [41].

In summary, it can be seen that a whole-life view of the holistic impact of spaces on human performance is currently buttressed on either side by studies using sensory perspectives within neuroscience-derived frameworks for the young and for the old. It seems highly likely that the "naturalness" dimension will be relevant across the board. The dimensions of "individualisation" and "appropriate level of stimulation" would be expected to be important, but maybe in varying ways, depending on individuals' ages and the contexts/activities involved.

4.3. An augmented analytical model

In the original configuration proposed [25], "individualization" was predicted to play out in two ways: particularization and personalization. "Particularization concerns accommodating the functional needs of very specific types of users [whereas] personalization concerns an individual's preferences resulting from their personal life experiences of spaces" (p. 224). In accommodating the extra complexity that comes with expanding consideration to a wide range of human groups and tasks it can be seen that the emerging left/right-brain dimension appears to be potentially relevant as a shared intervening variable. It could help to explain variations in the needs of school children studying different subjects, the elderly as their brains age and those at work depending on the novelty inherent in the tasks with which they are confronted. Fig. 2 gives this proposed analytical framework in diagrammatic form.

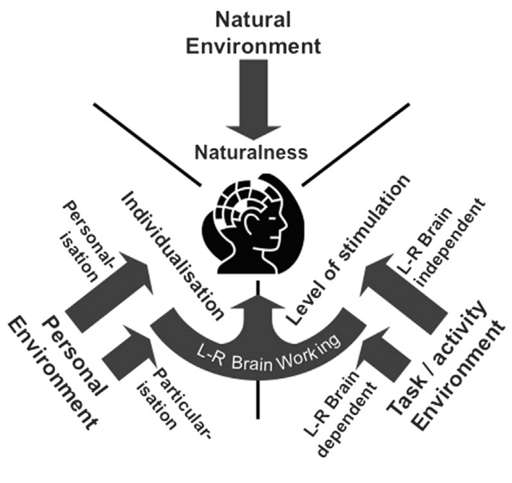

Fig. 2. Elaborated neuroscience-derived analytical framework.

Thus, it is anticipated that the neuroscience-derived structure utilised successfully for the analysis of primary schools will provide a sound foundation for the study of other life-stages, and there are strong indications that left/right-brain issues may provide a powerful enhancement to this analytical model. This, of course depends, in this context, on whether left/right-brain activities call for different holistic built environment conditions for their optimal support. The next section presents some initial evidence that throws some light on this question, possibly for the first time.

5. Initial evidence of distinctive left/right-brain environments

5.1. Reanalysing the data from the earlier study

In the published study of primary schools described in Section 3 [33] the pupils spent pretty much all their time in their own classroom. Because of this single location for all activities, the measure of learning progress used was averaged from their tests for reading, writing and mathematics. This made sense for this study, but presents the intriguing opportunity to re-analyse the data with progress in individual subjects as the dependent variables.

In Section 4 it was noted that there may be a lateralisation of brain activity such that grammar/reading reflect predominantly left-brain activity, in contrast to, say, mathematics that engages both sides more. So, using exactly the same data and multi-level modelling procedure as the above published study, but tuning it to focus specifically on the measure of reading progress, it was possible to derive the built environment factors (and pupil factors) that primarily explain the variability in learning rates in this distinctively left-brain subject area.

Setting out the statistical process in brief, analysis of the pupil progress data was carried out using a Multi-level Modelling approach [31] implemented at two levels: 'pupils' nested within 'classes'. This allowed regression analysis to be carried out at both levels to identify 'pupil effects' and 'class effects'. In the procedure a particular normalized improvement statistic (e.g. 'Reading Improvement') was investigated by first identifying the level 1 (pupil) covariates. Regression was done using several covariate factors including normalized start level, e.g. 'Reading Start', age-normalized start level, e.g. 'Reading Start on Age', gender and age. After the covariate regression had been done a second set of environmental regression factors were investigated that vary at the level 2, or class, level. The level 2 regression, therefore, identified the classroom environmental variables that are correlated with the particular improvement statistic. Along with the regression factors the procedure also allowed a measurement of the reduction in variance to be calculated for each of the levels. This is known as the Proportional Reduction in Variance or PRV. For comparison the overall R-squared value for the models was also calculated. As before the analysis is based on 751 pupils in 34 classes across seven schools in the Blackpool authority in the North of England.

5.2. Hypothesis and results

It is hypothesised that there will be some variation in the built environment factors that are important, depending on whether the subject/s in focus are general or specifically reading. The factors for reading would be expected to be different if primarily left-brain functioning does call for distinctive optimal environment conditions. Table 1 summarises the results of the analysis, performed as described above.

Table 1 shows that the Overall model, which is related to averaged improvement across all subjects, is correlated with the Naturalness parameter; Light, all three of the Individualisation

Table 1
Comparison of multi-level modelling outcomes by subject.

Models	Overall-averaged[a]	Reading
Level 1 pupil factors	Weighted start on age	Weighted start on age
	Weighted start	Reading start on age
		Reading start
Level 2 class factors	Light (12%)	Light (100%)
(plus % contribution	Choice (10%)	–
totalling 100%)	Flexibility (17%)	–
	Connection (26%)	–
	Complexity (17%)	–
	Colour (18%)	–
R-squared for model	51%	52%
PRV-Level 1 (pupil)	25%	33%
PRV-Level 2 (class)	73%	19%

[a] As reported in Barrett et al., 2013.

parameters; Choice, Flexibility and Connection, and the Level of Stimulation parameters; Complexity and Colour. It can also be seen from Table 1 that, as hypothesised, there are indeed some distinct differences between the factors that emerge for the Reading compared with the general results for all subjects. The general level of explanation of the models is similar at just over 50%, but for Reading the pupil-level factors are more influential and only one environmental factor, light, is found to be significant. It can be speculated that this reflects the nature of reading as an activity that requires deliberate focussing in. So, although the natural aspect of good lighting is still important, the stimulation from the other more active environmental dimensions is less relevant, and indeed, maybe these are within acceptable tolerances for this type of left-brain activity.

5.3. *Initial findings with big implications to be explored*

These findings may not be so relevant for primary schools where the same spaces are used for all subjects, although it may be possible to emphasise different aspects of the spaces at different times. But this is not the primary purpose of the analysis at this stage. The main point to emerge is that it would seem that optimal built environment characteristics do vary by subject and so, by implication, would appear to be sensitive to the intervening variable of left/right-brain emphases in cognitive activity. Of course deeper study of this aspect is needed.

However, this provides a degree of confidence in building on the enhanced neuroscience-derived analytical framework posited in Section 4 and applying it across a series of key life-stages. Before drawing this together into a vision for the development of a general model, the next section pauses to explore in more detail the overall research challenge set out in Section 2 within the key life-stages identified in Section 4. In each case the need to better understand the holistic impacts of spaces on users will be considered along with the issue of the choice of appropriate human performance metrics.

6. Challenges and human performance metrics by life-stage

6.1. *School pupils*

The general absence of research that links the holistic impact of school spaces-in-use to pupils' performance has been set out by Barrett and Zhang [42]. However, the potential negative impacts of poor classroom environments in use has been clearly evidenced, so highlighting the importance of addressing these issues [43]. Of course the study subsequently reported in Barrett et al. [33] makes a contribution to the research gap around holistic impacts in relation to primary schools. However, there is still a vacuum for secondary schools and here, interestingly, different subjects are generally studied in different classrooms. This accentuates the importance of identifying subject-related differences in the optimum environmental conditions, but also raises the methodological opportunity to study just this aspect.

For school pupils there are well-developed measures of learning that meet the criteria of being: established performance criteria that are objectively assessed and quantifiable [10], whilst also being meaningful and important to those affected. Of course there are strong arguments that there is more to education than progress on these formal learning measures, but there is no doubt that they are important and that findings about the built environment linked to them have immediate currency in practice. That said, learning is not the main performance metric for all life-stages and, in addition, different types of spaces (other than classrooms) and research challenges come into focus for other life-stages.

6.2. *The elderly*

As in the case of schools there exist many sources of information linked to health and ageing that variously: highlight single issue impacts [17], give strong views based on subjective interview data [44]; highlight practical issues [45] or provide a range of evidence-based examples [46]. Percival states that "domestic spaces have a significant influence on the scope that older people have to retain a sense of self-determination [and] that older people require adequate, accessible and personalised domestic spaces" (p. 729). However, Cama argues from an evidence-based perspective that "little has been studied about the impact the built environment has had on the elderly … [and asks] … can [we] turn to the evidence available from acute and long-term care and apply it to a residential application?" (p. 165). This seems quite likely as it is estimated that up to 85% of nursing home residents and 50% of those in assisted living suffer from dementia (p. 186).

Thus there are useful indicative ideas in relation to the elderly and their housing, but a holistic assessment of impacts remains a real research challenge [47]. This is an urgent challenge as over the next 20 years, the number of Europeans aged over 65 is expected to rise by 45% to 123 million by 2030 [48]. There is clearly potential to link to the work on hospitalised Alzheimer's care by Zeisel et al. [26] and to see if there are insights that can apply to the facilitation of independent living in individuals' own homes. Hospital accommodation for the elderly could be a focus, but the research gap seems to be around sheltered accommodation or care homes. The latter carries the methodological advantage of groups of people to study, but the disadvantage of more advanced medical issues than, say, sheltered accommodation, or indeed those still living independently in their own homes. Whatever the precise focus, residential accommodation or housing is clearly an important focus for studies of the built environment as it affects the elderly, for good or bad.

To be able to evaluate if the impact of the living spaces is positive or negative the appropriate human performance measure/s to be used needs to be well established and to reflect an important dimension of the quality of life of the elderly. Barnes et al. [49] review many frameworks and distinguish those that measure facilities and those that stress the contingent relationship between the occupant and the appropriateness of the space they are in (p. 778). Iwarsson [50] stresses the importance of responding to the characteristics of the people being studied in her "housing enabler" approach. It can be anticipated that the well established notion of ADL (activities of daily living) measures [51] will have utility in this type of study, covering "Basic" self-care tasks and "Instrumental" aspects related to independent living. Measures could be taken of the individuals at the start and finish of periods of occupation. The start measure would give an indication of residents' general condition, and the difference some insight into the dynamics of their quality of life. Additional surrogate measures could be sought, such as length of residence, calls on support provided, etc.

6.3. The workforce

As with the other two areas, there is a considerable body of work focused on office accommodation, however, a web based forum of over 450 corporate real estate and facilities management (CRE&FM) professionals displayed a collective view that "CRE&FM currently has no objective way of evidencing the value it brings to business" [52]. The great majority of the research that has been undertaken concerns the four basic environmental factors: temperature, air quality, acoustics and lighting. Kim and Dear [6] are a recent exception to this, primarily because their study was based on an existing POE database that included fifteen dimensions of satisfaction in offices. Interestingly "amount of space" and other layout/privacy issues came out with some of the strongest scores. Even these authors argue powerfully that there is currently no consensus as to the relative importance of internal environment quality (IEQ) factors for *overall* satisfaction. They also state that "there has been no previous research" on the nature of this relationship (p. 2013). So there is a real research challenge to identify holistic environmental impacts in the work place. This is compounded by increasing age-differentiation within the workforce, that is, the issue of multi-generational requirements as mentioned above.

For workplaces there are many possible performance measures with a focus mainly on individual and collective productivity, sometimes on creativity and to a reasonable extent on well-being. These are summarise by Clements-Croome [53] who goes on to say: "There are measures that can be quite easy to employ for repetitive office work … however, apart from basic qualities like speed and accuracy, it is much more elusive to assess quality" (p. 30). So performance in office situations can be studied within which repetitive, measurable work is carried out, such as for example processing insurance claims or proof-reading. However, it is acknowledged [10] that in general: "productivity is difficult to define" (p. 169) and that this is "a rich frontier for future … building research" (p. 176).

Given the importance of innovation to business success mentioned above (see Section 4), it is essential, but much more difficult, to measure impacts on innovative behaviour. From extensive experience Hodulak [40] suggests that spaces for innovation should provide for: communication, concentration, collaboration, flexibility, diversity and comfort. This complex of requirements reflects the almost contradictory nature of the innovation process which normally has to pass cyclically through expansive, creative stages and narrowing, implementation stages [54]. One way may be to study either organisations or spaces where creativity is at a premium so that various measures can be explored within the broad conceptual model proposed by Vischer [55], covering hard and soft measures of physical, functional and psychological comfort.

It can be seen that the work place is perhaps one of the more complex areas to study and design for. Age (multi-generational) issues crosscut with and are compounded by task/goal volatility (consistency v creativity). However, it will be seen in the next section that there are opportunities for insights to be drawn from the other two focal areas discussed.

6.4. Summary

Even the brief review above of each life-stage highlights that there are acknowledged research gaps in every case, to better understand the holistic impact of spaces on building users. In contrast there are significant differences in the spaces in question and the relevant measures of human performance. These range from: classrooms and learning for school pupils; to offices and productivity for workers; to housing and well-being for the elderly.

7. Vision for the development of a general sensory space design theory

Bringing the above discussion together into a vision for a whole range of life-stages it can be seen there are various elements. Taking a holistic multi-sensory perspective within a neuroscience-informed structure, the evolution of the human brain's functioning over a lifetime provides a golden thread (introduced in Fig. 1), anchored at either end by existing studies of those with young and with failing brains. This lifetime trajectory raises the issue of the added dimension of the balance of left-brain and right-brain functioning, which factors in variously at different life-stages. The range of life-stages that could be fruitfully studied is suggested in Fig. 3 against the background of the typical trajectory of the brain's capacities through life.

Fig. 3 shows a series of separate, but related, study areas. There is, however, tremendous potential for cross-learning from, for example, the secondary school childrens' subject-specific experience to illuminate left/right-brain issues for innovation-supporting environments in the work place or spaces to help the elderly maintain their independence. But of course the insights can flow the other ways too. This sort of meta-analysis could be an exciting area for development as more and more studies build upon those before, so populating a growing database of the environmental characteristics of a range of specific spaces and associated data about human performance in those spaces. This data set could be re-analysed at any point in a progressive drive towards a general space design theory for the entire human life-span. This would provide a "framework of understanding" symbiotically linking the more detailed studies [56]; both informed by them and more clearly contextualising them.

It is anticipated that the meta-analysis could be achieved in three ways. First, similarities and differences across the individual study areas could be tracked. It might be expected that aspects of "naturalness", such as daylight, would be quite consistent, but the implications of the varying appropriateness of different "levels of stimulation" could be highlighted, eg the use of colour and complexity for creative work v formal learning in school. Second, statistically derived models around cross-cutting issues, such as age-

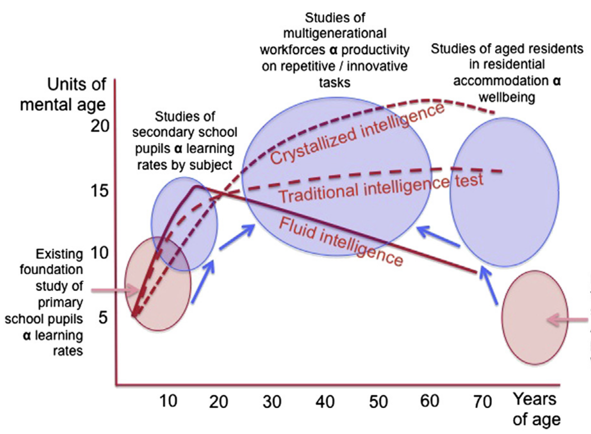

Fig. 3. Vision for the study of whole-life-stages sensory space design (Intelligence profiles drawn from Desjardins R and Warnke A 2012, p. 9).

related factors or tasks that involve lateralised brain functioning, could be explored and it is anticipated that more robust conceptions of these underlying "generative mechanisms" would be revealed through an iterative process of retroduction [27]. For example, it should be possible to discover if the implications about the optimal physical environment associated with a tendency towards left-brain thinking operates similarly for pupils studying reading and for the well-being of those getting into older age. Third, the multi-level modelling approach could be complemented by an exploration to detect novel, quite possibly non-linear associations between elements of the data set, using emerging statistical techniques, such as the maximal information coefficient (MIC) [57]. This last approach would address a major challenge, that is, to move from analysing the factors as they act holistically, to endeavouring to model the interactions between them. However, this should be more tractable once the initial step of identifying the factors in play that contribute to a holistic effect has been addressed to a greater extent.

8. Summary and conclusions

8.1. Summary

There is a general gap in knowledge around the holistic impact of spaces on human performance. Filling this gap demands that the conceptual and methodological complexity of real world users' experiences of built spaces is addressed. It is proposed that a potentially productive way forward is to use a holistic sensory approach in which a neuroscience-derived structuring is used to reflect the coordinating role of the brain. Example results have been highlighted, focused particularly on primary schools, but also around Alzheimer's care facilities. The potential of this approach to a full range of life-stages has been discussed and, beyond issues of naturalness, individualisation and levels of stimulation, the impact of distinctive left/right-brain cognitive functioning has been highlighted as being potentially important too. Here again an initial proof has been presented of variations in the optimal space characteristics depending on brain lateralisation.

The above train of argument has been brought together around a vision for the development of a general model for holistic sensory space design. This would address a number of life-stages at which different spaces, activities and human performance criteria are variously important. Through a progressive meta-analysis it is suggested that, over time, an evidenced, whole-life perspective on the holistic impact of spaces on human performance can be achieved. It is implicit in this perspective that multidisciplinary cooperation will be crucial to the success of the endeavour.

8.2. Potential impact

At a general level, evidence of the built environment impacting directly on social and economic issues is crucial to the European Construction Technology Platform's [58] aspiration to maximise the understanding of the *positive* contribution that the built environment can make by addressing value, rather than just cost considerations. This would also act as an input to the current ambition within the internal environment quality community to create more holistic international standards, where the scope of factors included is more inclusive and their interactive effects are better understood [5].

At a practical level, achieving double digit improvements, through evidence-based design innovations, on: the formative achievements of our children, the effectiveness of our workers and quality of life of our elderly, would be of incalculable value. The work on primary schools shows that many of the factors can be addressed immediately by users (eg visual complexity in the class), some in the medium term (eg wall paint colour), whilst others require input at the design stage (eg building orientation). By identifying clear evidence for holistic built environment impacts on human performance dimensions that matter in the "real world", a large range of stakeholders (users and designers) are very likely to be ready and willing to act.

This is an ambitious landscape for development, but it is suggested that there are sufficiently strong arguments, twinned with proof of concept results in key areas, to justify the expenditure of time and energy in this direction. If successful the results could be transformational.

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