Productivity in Buildings: the Killer Variables

Adrian Leaman [1] and Bill Bordass [2]

[1] Building Use Studies Ltd [2] William Bordass Associates
[1,2] The Usable Buildings Trust

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Introduction

This deals with the somewhat vexing question of human productivity in the workplace. Vexing because we do not think that this subject is as mysterious as many do. We set out to answer: "What features of workplaces under the control of designers and managers significantly influence human productivity?". The main theme is how individual occupants are affected. We are seeking building features which most readily improve or hinder human productivity at work. The findings can then be used in the briefmaking, design and management processes. We deliberately stick to factors which are in the direct control of building designers and facility managers; not to wider aspects like stress, lifestyle and organisational culture.

Our observations are mainly based on surveys carried out since 1985 in the UK by Building Use Studies and William Bordass Associates (hence the bias in the references). They also incorporate findings from the Probe series of building evaluation studies [Reference 1] with which we were closely involved. There is also a substantial wider literature, as reviewed by Lorsch and Abdou [References 2-4] and Oseland [Reference 5]. Most of these sources can be relied on, but there is also quite a lot written about productivity in buildings which has shaky foundations, so do not take everything at face value, especially exaggerated claims made about productivity gains.

Much is already known about how well people respond to different conditions of temperature, humidity, lighting, ventilation and noise, for example, and regulations for building design are based on many of such findings (although sometimes with a considerable time lag so that when legislation is introduced it can be out-of-date [Reference 6]). Many of these studies come from military, industrial and commercial sources. Although there is a reasonable consensus on key points, their findings can be contradictory and sometimes they can be hard to fathom. For instance, Reference 7 found that young people worked best (and were thus more productive) for short periods when they were uncomfortably cold. Periods of relatively uncomfortable arousal can thus be important. But it is unlikely that people will continue to perform well in conditions of prolonged discomfort, which begs the question of 'how long?'. Reference 8 shows that large numbers of office staff considered their working environments to be thermally unacceptable despite measured conditions falling within industry-standard comfort envelopes, so perceived and measured conditions can be different. Reference 8 also demonstrated that 23.5^{o}C is the temperature which people in offices prefer, but even with this there is a sizable minority of about 35 per cent who wanted it to be warmer or cooler, so minority needs cannot be ignored, although they often are.

Measuring and reporting on human productivity in workplaces is fraught with difficulty. For instance:

- Studies of individual occupants often miss out the wider context of physical and locational differences between buildings, and how they are managed and operated. For example, studies may examine the relationship between lighting and perceived productivity at work, but miss out completely other aspects of the buildings' performance, such as thermal conditions or noise, which not only may be more important factors but may also affect perceptions of lighting as well!
- Buildings and their occupying organisations are rarely even similar to each other from case to case, which complicates comparisons.
- Methodological and interpretational anomalies resulting from the first two points lead to problems with e.g. sampling and sample sizes, assumptions used in studies and spurious detail in the data collected so it can be difficult to filter out the most important points from case to case.
- It is also tempting to use weighting systems to try to iron out differences. For example, the length of time that people spend in a building tends to be inversely associated with their perceptions of comfort, health and productivity, so buildings with more part-time staff may show better scores. But weighting systems are hard to manage properly, and can be difficult to understand, so it usually

better to present the data in raw form without weightings, and explain the context clearly so that readers can make allowances.
- There is a growing tendency for building designers and managers to use promises of improved productivity at work as a carrot to attract clients, which means that they can become myopic about some of the research findings. For example, be especially careful about claims for productivity gains in supposedly 'green' buildings.
- It is impossible to measure productivity 'objectively' across a building in use; results have to be based on subjective responses of samples of occupants drawn from cross-sections of users. This is not to say that subjectively-obtained data are in any way inferior. It just means, as Gary Raw so aptly said: "In buildings. people are the best measuring instruments: they are just harder to calibrate".

Approach

On balance, we prefer the approach of "real-world research" [Reference 9] which deals with human activities in their real-life contexts (not experiments, laboratories or simulations which all have their place but are not real world in the sense we advocate). This involves:
- smallish surveys (10-15 buildings is an ideal number to discover most of the key points),
- but benchmarked against a larger sample to get truer comparisons;
- drawing on high response rates from the occupants surveyed (we like 90% response or better in each individual building to avoid bias in the responses),
- controlling for context through a thorough understanding of prevailing circumstances surveyed in advance through pre-visit questionnaires to facility managers,
- technical and energy surveys to provide operational detail,
- reporting based on "exceptions proving the rule" (that is, giving more attention to the unusual outcomes and understanding thoroughly why they occur).

This is the formula that was later developed in Probe [Reference 1].

Buildings are complex systems made up of physical and human elements with many associations, interactions, interfaces and feedback loops. Elements and interactions create "emergent" properties [Reference 10] like aesthetic qualities which are often greater than the sum of their parts and consequently harder to pin down, describe and analyse. Because of interdependencies, it is often fruitless to try and separate out different variables and treat them as "independent" in the sense that statistical methods often require. Building characteristics like depth of space from wall to wall, open-plan space and air-conditioning all depend on each other's presence to a greater or lesser extent, so they cannot be independent in the statistical sense: they are associated because they are all part of a building. Similarly descriptors like health, comfort and satisfaction are usually associated with each other. As a result, they produce cats' cradles of statistical interdependencies. Multivariate statistical techniques, which are supposed to help simplify these complex relationships, often have a nasty habit of throwing back your own confusion in a reorganised form.

Another pitfall is to muddle association with cause. For example, if a study shows that outside awareness of hospital patients is associated with more rapid recovery rates it does not necessarily mean that all patients should be given more windows to look out of, nice as this might be! Because of autocorrelation in the data, it is quite easy in productivity studies to show positive and significant relationships between variables. A common one is the association between the presence of natural lighting and perceived productivity. However, placed in the wider context of the building's overall performance, natural lighting may be relatively unimportant, with a far stronger effect created by e.g. summertime ventilation. Because some studies look at lighting variables only, they may miss out more important variables elsewhere in the total system.

As well as physical complexity of the building itself, designers, managers and occupiers obviously also have different preferences, priorities and personal agendas. Changing circumstances add to the richness and dynamism of contexts, but also make them less yielding to conventional analysis. Although it is tempting to seek out general theories governing behaviour in buildings (and enshrine principles in design guidance and building legislation), in practical terms constraints imposed by contexts frequently turn out to be more important for the designer, manager or occupier. For example, noisy offices can wreck best intentions elsewhere in the design.

Contexts - locational, social, economic, technical and environmental - are always subtly changing, and can sometimes have surprisingly direct effects on local situations. For example, it can be baffling why two schools - identical in design and intake profiles and on adjacent sites - should differ markedly in vandalism damage rates. This can often be explained by environmental strategies employed by the on-site building managers - especially with respect to the speed of repair of damage and the extent to which particular individuals take responsibility for ("own the problem") of repair [Reference 11]. This example might tempt a designer to say that management is the cause, not design. However, as performance evaluation studies show, buildings whose management strategy has been developed from the outset of the design, with a clear understanding of client requirements and management capacity, are more likely to perform better. Hence management and design factors, like many others in buildings, depend on each other and often cannot be meaningfully isolated in real situations [see Reference 12].

Designers and managers constantly strive to create conditions which bring out the best in people and add value to investments and services. As Patrick Nuttgens put it: "to make something out-of-the-ordinary out of the ordinary". Occupants also like to have a niche for themselves which suits the task they have to carry out. To further complicate matters, designers, managers and occupiers can all behave perversely. For example, in a study of the top floor of an office building we asked the occupants "Why do the lights always seem to be on when you don't need them, especially as the switches are easy to reach?". The reply came: "We only do it to annoy the manager. He is obsessed with switching off the lights, so we switch them back on again whenever he goes out just to annoy him."

Too often, though, elements unwittingly interact and conspire to create unforeseen and unwanted problems. In the context of technology and its side-effects, Edward Tenner has memorably labeled these "revenge effects" [Reference 10]. In buildings, technical elements often work reasonably well in isolation or in theory, but when included as part of a wider system of operation induce inefficiencies which ultimately affect the ability of people to perform their work properly. These wider aspects of the design, use, management and operation of buildings concern us most here.

Terminology

By "productivity" we mean the ability of people to enhance their work output through increases in the quantity and/or quality of the product or service they deliver. The intention is that productivity is positive in the sense of better or more output. However, it is just as possible to go the other way and produce less. In the buildings that we have studied, about two thirds of them exhibit 'negative' productivity, i.e. against some internal reference occupants on average think that facilities and conditions in the building reduce their perceived productivity.

In buildings, we would ideally like to assess the productivity of all the occupants by some kind of measured means, such as counting keystrokes on a computer. However, this is obviously impossible for most kinds of building users as not only are their work tasks not measurable this way, but any measures that might be devised would not capture the full richness of their task and the circumstances in which it is carried out. How can you compare, for instance, the productivity of operatives in a call centre with that of their managers?

The answer is to use scales of perceived productivity which can be answered by everyone from cleaners to chief executive, rather than attempt to measure productivity directly. The question on productivity which has been incorporated into most Building Use Studies questionnaires since the pioneering Office Environment Survey [Reference 13] of 1987 is shown in Figure 1. It is the subject of much comment, often from those who would prefer 'objective' measures. We know that the question is not perfect, and might be improved upon one day. We are happy to adopt any improvements as soon as they are forthcoming. But as yet, there have been none!

On balance, advantages with subjective perceived productivity scales outweigh disadvantages.
Advantages include:

- a single question covers the topic so it can be incorporated in surveys with wider objectives (although we find that building managers are still wary of the question and sometimes veto it);
- the question is common to all respondents so that fair comparisons can be made between most of them;
- it can be incorporated in questionnaires across different building types (although strict comparability between types may need to be treated circumspectly, for example between teachers and administrative staff in a school where working conditions are different between the two);
- large samples may be surveyed relatively cheaply;
- benchmarks of averages or medians may be used to assess how occupants' perceptions in individual buildings score against the complete dataset;
- data analysis and verification is easier across large samples in many different buildings.

Disadvantages include:

- the nagging doubt that perceived productivity as measured may not associate well with the actual productivity of the occupants (although many agree on the key point that perceived and actual productivity are strongly associated (see the review of sources in References 3 and 14));
- the need for occupants to judge their own reference points when answering the question (they sometimes want to know "Productivity with respect to what?" - we assume that their past experience of using buildings is the reference point);
- the possible effects of context and other ruling factors at the time of the survey, for example, rumours of possible redundancies (although we tested this in an unpublished building study in 2003 and found that there was no difference in satisfactions scores between a department recently made redundant and people in the rest of the building).

Objectives

The main objectives of the productivity parts of building performance studies are to:

- give designers and managers indications of the main factors within their control that might influence human productivity at work;

- help prepare design and management strategies which measurably aim to improve performance for organisations and individuals without compromising individuals' needs and introducing unhelpful side-effects.

Our emphasis is always on appropriate design and management strategies as expressed in the design briefing process and troubleshooting studies, and the major risk factors affecting productivity. We are not attempting a "theory" of productivity at work, nor a detailed analysis of cause and effect or costs and payoffs. These require a different approach. Bear in mind that the productivity question is only one out of over sixty questions on the standard Building Use Studies occupant survey.

"Killer" variables

In technical language, a "killer" variable has a critical influence on the overall behaviour of a system. Here, killer variables are those that affect perceived productivity most.

From our own work, and from the literature, we can guesstimate that productivity gains (or losses) of up to about 20 per cent may be attributable to the effects of buildings on their occupants. Much of the data comes from office buildings, but it can be any type of building with a permanent staff. Fifteen per cent gains/losses as a ballpark figure crops up in the work of Brill [Reference 15] and Vischer [Reference 16], for example. Lorsch and Abdou talk about the productivity of 20 per cent of office workers in the USA being raised simply by improved indoor air quality [References 2-4]. Data from the Probe studies show perceived differences of up to 25 per cent between comfortable and uncomfortable staff, with uncomfortable staff showing consistently lower productivity (as common sense predicts - unless the arousal mechanism is more important) [Reference 1]. The difference gets narrower as overall satisfaction with the building improves. We have come across claims of productivity improvements as high as 40 per cent, but it was impossible to inspect the methodology used, so we ignored them.

Whatever the actual figures (no-one knows, of course) there is consensus that indoor environment factors improve output, as well as a lot of evidence to show associations with a cluster of related factors such as perceived health, comfort, and satisfaction. Our map of the main variables is shown in Figure 2. For a more speculatively theoretical account, see Reference 21.

Our list of "killer" variables has now reached five. Each represents a group of features which have more connections amongst themselves than with the others. They are discrete but only to some extent: there is no such thing as an independent variable in a building! Their order of importance depends on prevailing circumstances - the building design, perhaps, or the way people are treated by management.

The killer variables [1] are:

1. Comfort, including personal control.
2. Responsiveness to need, including comfort (from 1.), but a host of other ways in which needs should be met effectively.
3. Ventilation type, which also encompasses attributes such as size, building depth and other allometric properties (i.e. how size affects shape, volume, services etc.).
4. Workgroups and their layout in the space plan.
5. Design intent, and how this is communicated to users and occupants.

Comfort, including personal control

Research work in the 1980s into what was then called sick building syndrome [2] confirmed to a new generation of researchers what was already well known to an older one - that people's perception of control over their environment affects their comfort and satisfaction. Work on thermal comfort, notably that of Humphreys and McIntyre in the 1970s [References 22-24], had shown that the range of temperatures that building occupants reported as "comfortable" was wider in field studies than in controlled conditions in the laboratory. People seemed to be more tolerant of conditions the more control opportunities - switches, blinds and opening windows, for instance - were available to them. This is a vital finding to take from pioneering thermal comfort research and is the basis for what later came to be called 'adaptive comfort theory'. People are more forgiving of discomfort if they have some effective means of control over alleviating it. However, many modern buildings seem to have just the opposite effect. They take control away from the human occupants and try to place control in automatic systems which then govern the overall indoor environment conditions, and deny occupants means of intervention. On the rare occasions when such systems can cope with all eventualities, they can work wonderfully well but, often as not, they do not. [Reference 28]

The extent and strength of relationship between comfort and productivity (using the BUS variables 'overall comfort' and 'perceived productivity') is shown in Figure 3. The more comfortable people say they are (averaged for each building in the dataset) the more productive they say they are (again taking the average score for each building). 'Overall comfort' is an umbrella variable which covers peoples' perceptions of heating, cooling, ventilation, lighting and noise taken together in an overall assessment.

Similar results on the relationships between perceived control and sickness symptoms have been reported in, for example, Reference 25. In studies on heart disease in civil servants, higher incidence of heart attacks seem to be related to people's perception of control over their work [Reference 26]. There are numerous other such examples, including the revived interest in the 1990s in adaptive comfort [for example, Reference 27].

(1) These differ from earlier versions of this paper in that 3. Building depth is renamed Ventilation type, Design intent is added to the list as number 5, and 1. now embraces a wider interpretation of comfort.

[2] Now termed building-related ill health.

Figure 4 has results for office workers in 11 UK buildings examined by Building Use Studies in 1996-97. Self-assessed productivity (see Figure 1) is significantly associated with perceptions of control in 7 out of 11 buildings. Perception of control is measured by the average of five variables for perceived control over heating, cooling, lighting, ventilation and noise.

Figure 5 shows that the relationship in Figure 4 probably gets weaker as buildings perform better - that is, there is less need for individuals to have means of discomfort alleviation when base conditions are good.

Figure 6 shows that of the five perceived control variables - heating, cooling, lighting, ventilation and noise - the last, noise, is most strongly associated with perceived productivity, but the relationship is quite weak. Even so, perceived control over lighting is the only one that is not significant.

Figures 4-6 tell a stark statistical story about personal control and productivity. Building users in their personal comments on questionnaires are much more forthcoming. In study after study, people say that lack of environmental control is their single most important concern, followed by lack of control over noise. Taking one typical comment from many in the same vein from a building study carried out in 1996: "Noise has the most disturbing effect on my work. Other factors such as heat and light are not so disrupting." People often oppose the introduction of open-plan working because they suspect that they will lose control and privacy, and it will become more noisy. This might not necessarily actually happen in practice, but people are afraid that it will.

In spite of the wealth of research and occupier evidence that high perceptions of personal control bring benefits like better productivity and improved health, designers, developers, and sometimes even clients seem remarkably reluctant to act on it. There are many reasons for this, including the absence of thorough cost-in-use analysis in the calculation of future payoffs (and the problem of who actually receives the benefit). Four are prominent.

1. Environmental control operates at the interface between a building's physical and technical systems and its human occupants, or, less visibly, automatically and often under the supervision of computer-controlled building management systems. Perhaps seduced by the promise of technology rather than its delivered performance, designers assign more functions to automatic control than are usually warranted and, knowingly or not, make the interfaces obscure. They then often do not seem to make clear to the client the management implications of the technology, and whether these are acceptable to them. Simpler and more robust systems are required, with greater opportunities for users to intervene - especially for opportunities to override existing settings, better feedback on what is supposed to be happening and whether or not the system is actually working [Reference 28]. This point is picked up in more detail later under design intent.
2. Building design is split into architectural and building services tasks, often with surprisingly little integration between them. Poor attention to detail in building controls is a common symptom of an incomplete design and specification process with gaps between areas of professional responsibility. As well as lack of recognition of the problems here, there is also an absence of tools for specification and briefing, and absence of suitable standard componentry and systems. Manufacturers find it difficult to invest in suitable new or modified products to meet such requirements, owing to a diffuse market with no well-articulated demand. Those who have tried have found success elusive. For example, the promising environmentally-advanced Colt window system was taken off the market as a complete package [Reference 29].
3. Designers do not fully appreciate the important difference between comfort provision and discomfort alleviation. For example, the ability to alter the position of the computer screen - a seemingly trivial feature - can be crucial to office users' comfort. By making tiny changes to their immediate environment to mitigate the worst effects of (say) glare from the winter sun, or down draughts, occupants can turn intolerable conditions into marginally tolerable ones without undue management intervention. Most control adjustments are at margins of discomfort, triggered by something experienced as uncomfortable, rather than in anticipation. The absence of this capability to fine-tune, especially in space-planned offices with fixed furniture systems and little or no user control, can be make the difference between tolerable comfort and dissatisfaction.

4 Sadly, few building occupiers are motivated enough to take the bull by the horns and gain control of systems which are troublesome. As a result, chronic problems multiply and eventually become difficult to reverse, even though, individually, they may be easy to remedy. For example, a problem which we have observed in building after building is doors which close too loudly because their automatic door closers are set too powerfully and there are no noise dampers in the door frame. The closers also squeak, so that every time anyone uses a door it first squeaks, then bangs shut. This happens countless times, and affects all those unfortunate to be sitting in the vicinity.

Responsiveness to need

To many people, the relationship between better personal control and human performance is common sense; so too is the cluster of variables related to responsiveness. Many of the buildings which work well in post-occupancy studies appear to have the capability to meet people's needs very rapidly either in anticipation or as they arise. This applies to personal control, but it also works at other levels: the ability to reconfigure furniture, for example, or adaptability of spaces to accommodate change, or speed of response to complaints by the facilities management department.

The importance of responsiveness first became clear to us in a study in 1992 which included One Bridewell Street, Bristol [References 30 and 31], revisited by Joanna Eley in 1996 [Reference 32]. This building is noteworthy because, although air-conditioned, it uses (or at least used to use, circumstances have changed) little more energy than a good-practice, naturally-ventilated, open-plan office. In addition, occupant satisfaction was unusually high. Was this just coincidence or was there something more profound at work? At One Bridewell Street high occupant satisfaction seemed to be related to the speed with which the facilities management department dealt with complaints of discomfort: the response was exceptionally fast, and occupants were told exactly what the outcome was. The facilities manager also learned to anticipate common problems and to deal with them, often before anyone noticed. Personal control for the occupants was not high, with just infra-red "zappers" for the lights and limited ability to change workstation position.

To test the possible influence of response time, a new variable was added to the Building Use Studies questionnaire in 1995 (Figure 7). The relationship between perceived speed of response to complaints and perceived productivity is shown in Figure 8 and people's perception of "quickness" (the speed with which occupants think that heating, cooling, lighting, ventilation and noise needs are met) in Figures 9 and 10.

With the usual interpretational caveats relating to small, non-random samples, the results in Figures 8-10 are grounds for developing this line of of analysis further. The association between speed of response and productivity in Figure 8 is positive and significant. Eight out of 11 buildings in Figure 9 shows significant positive associations between perceived quickness of response and perceived productivity. Figure 10 shows that, just like perceived control, the strength of correlation between quickness and productivity increases as the buildings' overall performance decreases. An obvious conclusion from this is that quickness and control are also strongly and significantly associated and this indeed is the case (for individuals rho=0.60, p=0.0001; for building means rho=0.75, p=0.0125).

As measures of response time and personal control are themselves related, are we dealing with two sides of the same coin? To some extent, yes, because responsive control delivers rapid response by definition. But in some buildings a lack of individual control facilities is more than compensated for by the excellence of the facilities management arrangements. Conversely, if designers try to add control in a complicated building which already lacks management resources their efforts may well be defeated as there will be less capability to manage the added complexity, which will induce further chronic failures.

Most buildings tend to have poor levels of perceived control because they also have relatively low levels of building management: it has been incorrectly assumed at briefing and design stages that building services technology will automatically deliver what the occupants require without undue extra management intervention or, alternatively, that management will be superhuman.

As the Probe studies [Reference 1] show, these assumptions are wrong. The buildings that came out best overall either managed technological complexity with high levels of expertise (e.g. Tanfield House) or deliberately rid themselves of gratuitous complexity and over-dependence on management intervention [e.g. Woodhouse Medical Centre].

So designers and managers should consider both personal control and response time implications, rather than think that they are the same. Building Use Studies has found that when something goes wrong occupants give building managers the benefit of the doubt for a honeymoon period of up to three days, then get upset or give up! [Reference 33]

The implication is that real-time responsiveness is something to be considered in the briefing and specification processes, and that different response time standards could be set for different occupier needs. For example, glare and severe overheating need to be dealt with and corrected immediately, whereas a three-day threshold could be used for the replacement of components which directly affect interfaces - simple things like blinds, chairs, luminaires and suchlike.

Ventilation type

The third killer variable is ventilation type. We have found that:

- the deeper buildings get, overall satisfaction and productivity tend to go down;
- a depth of about 12m across the building seems optimal for human performance variables;
- shallower plan forms tend to cost about £50/m^2 more, assuming similar cost levels per unit area of envelope and for building services. However, shallower-plan buildings may lend themselves to cheaper, more domestic envelope construction and cheaper services. Unfortunately, cost calculations often find it difficult to consider such trade-offs; economic calculations tend to be more precise at minimising envelope-to-floor-area ratios than building services costs, about which they tend to be less well informed [Reference 34].

Ventilation type is closely related to building depth because mechanical services have to be added whenever buildings get deeper than about

15m across, the limit of simple natural ventilation. Buildings have allometric (size and depth) properties which make them disproportionately more complicated to service as they get bigger. This is not just a matter of building services like mechanical ventilation and air-tempering, which are always needed with depths greater than 15m., but also spatial and behavioural complexity - there are many more activities and much greater likelihoods of conflicts, in bigger floorplates with higher populations, and a higher dependence on technology and management.

Looking at differences in perceived productivity in the 2004 UK Building Use Studies dataset, the mean perceived productivity score for all UK buildings is minus 2.1 per cent (Figure 11). Broken down by ventilation type the scores are minus 2.5 per cent for natural ventilation (NV), minus 2.4 per cent for air conditioned (AC) and minus 2.4 per cent for advanced natural ventilation (ANV). Mixed-mode (MM) (0 per cent) gives better perceived productivity scores. Note that none of these averages is greater than zero. Overall, only in some 30 per cent of buildings in the dataset do occupants, on average, report scores above zero. The naturally ventilated buildings have higher standard errors, implying that their range of performance is wider.

The pointers are that occupants prefer natural ventilation as the default - in winter, spring and autumn - and air-conditioning, not surprisingly, in the hot, humid parts of summer [Reference 35]. Ventilation type is also a correlate for other variables which affect human performance. Many of these have been assessed, although not necessarily in working buildings or conclusively. They include:

- occupants' preferences for window seats (studies usually show that people with window seats tend to be more comfortable but this effect tends to decrease as overall building performance improves);
- ill-health, with the statistical association of chronic, building-related ill-health symptoms (like dry eyes or stuffy nose) with larger buildings leading in the 1980s to wide speculation about the role of air conditioning as a cause. It turned out to be more a matter of how much management an occupying organisation was prepared to put into a building to deal with chronic problems that arose in circumstances where people were more dependent on the quality of the building, its systems and its management.

Building depth introduces a double-edged effect. As buildings get bigger, they are capable of performing more functions and more people can be packed in, but the penalty is increased operational complexity which creates a greater likelihood of failure - especially chronic performance problems - which in turn increases the cost of management to reduce relative risk. On the other hand, people do not like working at high densities (with the exception, perhaps, of financial dealers who seem immune) but higher densities are often perceived to be needed to "save" on office costs. When this trade-off is made in reality, building users opt for lower densities because this gives them sufficient degrees of freedom to deal with the consequences of dysfunctional conflicts. What do you prefer: an aircraft or theatre with 70 per cent of the seats filled or completely full up? [Reference 36] We had a clear case of the cocktail party effect (where conditions rapidly worsen as densities rise) in a case study in 2004. People were moved in to a new building sequentially. Early movers reported that they liked the building for the most part, but that once planned densities had been reached after about twelve months conditions had become noticeably worse.

Workgroups

The fourth killer variable is workgroups, remarkably, given their prevalence, one of the least understood topics in modern buildings. [Reference 37]. In offices, perceptions of productivity tend to be higher in smaller and more integrated workgroups. Like control, this will be obvious from personal experience: given an unrestricted choice most will opt for their own room, for instance, or a small workgroup with a few colleagues. This said, there is little research data to back it up and, like other aspects of the effects of density and size, needs more work.

In a rare case study building we had data where both productivity and workgroup topics were included. In this single instance, workgroup size was able to explain differences in overall comfort (smaller was better, as might be expected), but there was no association between size of workteam and overall perceived productivity for the individuals in the study building. Obviously a sample of one is not enough evidence.

Figure 12 has some data from a bigger sample, . It shows overall comfort scores broken down by the number of people that occupants say they sit with - a possible surrogate statistic for workgroup size. Again, the indications are that people are less comfortable as workgroups get bigger. As perceived comfort and perceived productivity are strongly associated, it is to be expected that workgroup size and perceived productivity are also (inversely) related. However, we should stress that this is only a hunch: we do not have further evidence.

The effects of workgroup size will be hard to demonstrate properly because there is a lot of autocorrelation in what will be 'noisy' data. The true effects will be hard to filter out in a more telling analysis. For example, the effects of status (senior managers will tend to have their own offices), open plan (bigger open plan spaces may have bigger workgroups) and density (workgroups that are crammed together) may all introduce side effects of their own.

Our confidence in including workgroups as a killer variable came from work in 1987 [Reference 38]. Room size is a correlate of perceived control for temperature, lighting and ventilation, with perceived control declining with workgroups bigger than about 5 people. As perceived control is a correlate of perceived productivity, it is fairly safe to assume that workgroup size is also a contributory factor (but so are technical factors).

From a design and management point of view, workgroups are seen as desirable both for space saving reasons (possibly spurious, see above) and for better communication between colleagues. There is always a trade-off to be considered between the risk of degrading performance in open plan and cutting people off from each other by putting them in their own rooms. Designers and managers both tend to opt for the open-plan approach, but for different reasons. The evidence we have indicates (but does not prove) that well-integrated workgroups of four to five people will probably be acceptable, but the risks of lower productivity in bigger workgroups can increase substantially thereafter. To support the claimed business benefits it is therefore necessary to put in a much higher level of expertise in building and services design, and facilities management. While we all know this to some extent, the degree of improvement necessary can be much higher than one would think.

A key reason is the "mapping" between the workgroup's activities, the available environmental controls and zones of services. Where the relationship is one-to-one (i.e. everything coincides as it should in a single room) the sole occupant will have full control over lighting, blinds, ventilation, heating, cooling, privacy and noise, and is able to fine-tune to suit needs exactly. Here there will be perceived productivity benefits for the occupant who will be able to prevent undesirable impacts like distracting noise or overheating. Supervising managers may be rather less keen on individuals with high levels of privacy and productive interactions may also be reduced but modern technology is permitting close work integration with less face-to-face contact.

As workgroups get larger, the occupants might be affected in these ways:

1. What mapping there is between environmental controls, services zones and activities breaks down even further (for example, the lighting may be switched for the whole floor rather than for workgroups alone).
2. Occupants also have to consider their colleagues' wishes when they want to make changes. As a result, the likelihood that everyone will be satisfied with the prevailing settings will reduce as the workgroups get bigger, but equally most people will be inhibited in taking any action to change conditions unless they become completely intolerable. This is an inevitable consequence of a) size and allometry; b) differences in individual preference ranges.
3. Remote effects become important: for instance, glare from a distant window, possibly even through a glass partition, or draughts of uncertain origin owing to complex movements of air in both naturally-ventilated or air-conditioned spaces.
4. There is a greater likelihood that primary and secondary circulation routes will break up workgroups, often cutting through the middle of them.

The best strategies for the designer and managers are thus to:

- keep workgroups as small and well-integrated as possible;
- make sure that zones of activity map onto the service zones, especially for productivity killers like irrelevant noise, glare and draughts;
- keep sources of unwanted distraction down to a minimum (we have found that up to 60 per cent of staff sitting in open-plan offices can be located directly next to a source of random distraction like the end-doors which may squeak and bang when closing, the photocopier or the tea/coffee area); but
- do not interfere with sources of relevant information, that is information that is needed for work tasks within earshot and lines of sight, so that people receive useful information by default; and
- design and manage the overall worksetting so that the default (i.e. normal) setting is reasonably comfortable, safe and healthy and does not rely on excessive amounts of technological or management input to make it work acceptably.

Design intent

Design intent is the last of our killer variables, although it is more a key to help understand how the other variables tie together. By design intent we mean:

- How designers intend particular features incorporated in a building are supposed to work, including how they should be operated and the circumstances in which they should be used.
- How users interpret this, if at all. Features might be included which may work well if only they were actually used but which are completely transparent to the users because of some design or management flaw (e.g. trickle ventilators in windows are often ignored by users because they do not see them, and even if they did see them they do not know what they were for).
- The relationship between design intention and actual use (hopefully they coincide).
- The actual effect produced, which may not necessarily be the intended one!

Donald Norman, speaking more generally about all types of everyday artifacts [Reference 39], calls the first three the "design model", the "users' model" and the "system image". Norman says that the user acquires all knowledge of the system from the system image.

At one level it is obvious that design intent is important because how else will things be used properly [Reference 40]? However, many designers make the false assumption that the way they see things (their "design model" in the sense used by Donald Norman) is the same as users (the "users' model"). Designers tend to know much more about how constraints affect design decisions and know the reasons why things are as they are, reasons which are usually unknown to the users. Their designs are outputs from a process. Users have little or no knowledge of why, only how designed objects work as inputs which affect the tasks they have to carry out. These mental models are often very different.

From this it should follow that buildings will perform better as a result of good usability: viz better perceived productivity. We take this as a given. However, we are saying a little more than this.

- We know that people are more forgiving of uncomfortable conditions when they have more perceived personal control, even if those conditions may be objectively poorer than they might otherwise have been (e.g. they tend to opt for possibly poorer indoor environment conditions in naturally-ventilated buildings over more tightly-controlled air-conditioned). This is a fundamental finding from thermal comfort research. The tendency has been to think that this tolerance or 'forgiveness' is the result of having more control. However, this may be a mirage. Naturally-ventilated and mixed-mode buildings tend also to be simpler for users to understand and operate (although this is by no means always the case), so that design intent tends to be better communicated to users. Because users understand better what ought to happen, they are more tolerant if actual performance does not quite live up to expectations.
- In studies of buildings which have occupants who are themselves designers, we find that the occupants also tend to be even more tolerant, while one might have expected them - knowing how the design might have been better - to have been more critical of under-performance. This comes from our own (unpublished) work on office buildings which are occupied by design practices and research organisations. The clients for these studies usually are in trepidation about the results, because they think informed designers or researchers will know more about the building, and therefore be much more critical. In fact, we usually find the opposite. The designer occupants tend to be less critical possibly because they, as knowledgeable users, understand design intent better!
- We also know from our own work in Probe and other studies that there is a subset of buildings which have high levels of both perceived productivity and energy efficiency. What possibly connects these seemingly dissimilar variables?
  - Energy-efficient buildings, especially those that are shallow-plan with natural ventilation, are often intrinsically simpler and have features which users tend to like anyway.
  - More care is often taken in their briefing, design, construction and subsequent management and monitoring, so that there is a greater likelihood that means and ends work in harmony and that targets set in the brief are actually met in the final building making all-round performance better.
  - They have more components which users operate themselves.
  - It is often easier for users to comprehend their functions.
  - They may be simpler and easier to manage.
  - In those of them that require high levels of management, the management is committed to deliver both staff satisfaction and high energy efficiency.

  Be careful though. Do not make the mistake that energy-efficient buildings "cause" improved productivity - if any relationship exists then it will be an association not a cause. And do not mix up energy-efficient buildings with 'green' buildings! Just because a building is called 'green' does not necessarily mean that it will be energy efficient in actual use.

Conclusion

We have dealt with productivity in the workplace from the perspective of things within the control of building designers and facilities managers. Necessarily this means missing out aspects of productivity largely or entirely outside the influence of building professionals. These include considerations like workplace stress (which we once tested to see whether stress was building-related, and found that for most intents and purposes it was not [Reference 41]), management attitudes and job satisfaction [Reference 42].

Although the concept of productivity begs many definitional and methodological questions, we think that the available data are robust enough to tell a clear story which designers and managers can practically incorporate. Buildings, especially offices but this applies to all buildings with permanent staff, work best for human productivity when there are:

- many opportunities for personal control, providing a background for healthy, comfortable and safe operation as well as adaptive comfort;
- a rapid response environment, not necessarily only for personal control, but for the many other aspects of a buildings' operation that might compensate for absence of personal control, such as an excellent complaints monitoring and feedback system;
- natural ventilation of some sort, best of all incorporated in a mixed-mode scheme with which mechanical systems are properly

integrated and managed, and able to take the load where the natural ones are inadequate.;

- shallow plan forms, preferably demanding less technically complex and less management-intensive systems (with the added benefit of better energy performance);
- proven energy efficiency, which apart from the obvious benefits of lower emissions, also tends to be associated with better briefing, management and monitoring which ultimately impacts on better human performance in the workplace;
- activities which properly fit the services which are supposed to support them, not only in spatial capacity (I.e. enough room for everyone), but for the zoning and control of heating, cooling, lighting, ventilation, noise and privacy;
- clear communication of design intent to users, so that users of all types (not just the permanent staff) understand how things are supposed to work, can intervene to change things if necessary and get rapid feedback on whether more not the change had actually occurred.

In some circumstances, not all these will not be possible or desirable. This is perfectly acceptable, but clients, designers and managers then need to appreciate the extra levels of core and support services that will be needed to produce good performance.

Ideally, simple, shallow plan forms, small work rooms, robust and manageable controls and domestic levels of servicing work best. In fact, Raw and Aizlewood show in Reference 43 that building-related chronic illness was significantly lower (and perceived comfort higher) in homes than in offices - just what would be expected from our findings.

However, such "ideal" design forms (characteristic of offices in the UK up to the 1960s) have long since been superseded. The relentless trend is now towards intensification (and diversification) of building use [Reference 44] with much greater attention paid to:

- risk/value payoffs not just in rental or property investment terms as in the past, but for the wider canvas of human and environmental resources as well;
- business benefits and consequential environmental disbenefits which have to be managed if overall performance improvement is to be achieved;
- design strategies linked far more closely to business missions to improve strategic advantage in the market place and often also to cost reduction;
- greater interest in "generic" spaces and forms of servicing which allow rapid switching between different occupier activities.

Bigger and more complex buildings demand subtler strategies for managing this complexity and different design strategies and technologies to support them. Where this is successful, performance gains are possible, but where management does not properly compensate for the extra diligence that technology needs, chronic problems usually result.

The trend towards mixed-mode buildings (with mixtures of natural ventilation and air conditioning) is a case in point. Treating findings from Probe and other building evaluation studies circumspectly, it seems that mixed mode can offer the best of both worlds - better occupant satisfaction and better environmental performance - and occupants can detect the differences. Studies by Rowe and colleagues in Sydney [Reference 35] suggest that mixed-mode offices not only give performance advantages through better thermal comfort and better perceived ability to perform work (i.e. better productivity), but they are also better for perceived air quality and overall satisfaction with workplace. As with British studies, the work also confirms that this delivers better perceived control and leads to much improved energy efficiency. By monitoring the switching behaviour in mixed-mode buildings, Rowe has shown that a control-rich, naturally-ventilated environment is the preferred default - even in sub-tropical conditions in Australia - and this preference is only abandoned on the minority of occasions when both temperature and humidity exceed tolerance thresholds. However, it is possible to get mixed-mode strategies and engineering wrong too - as a number of studies have shown, in particular where the details have not been worked through carefully enough.

Although we can be upbeat and report these findings optimistically, we have also tried to show where things work and where they do not. Unfortunately, the design and construction industries are much more coy, especially about failures. They tend to report just the good news and forget about the downsides, which often turn out to be the very things that affect human productivity the most. Many of the matters we have dealt with here have been known about for generations. Poor human productivity in buildings is a function not just of our five "killer" variables but also poor professional feedback, lack of integration in design processes, lack of care for the primary occupants, weak or non-existent briefmaking and the convenient but disturbing tendency to forget the bad news.

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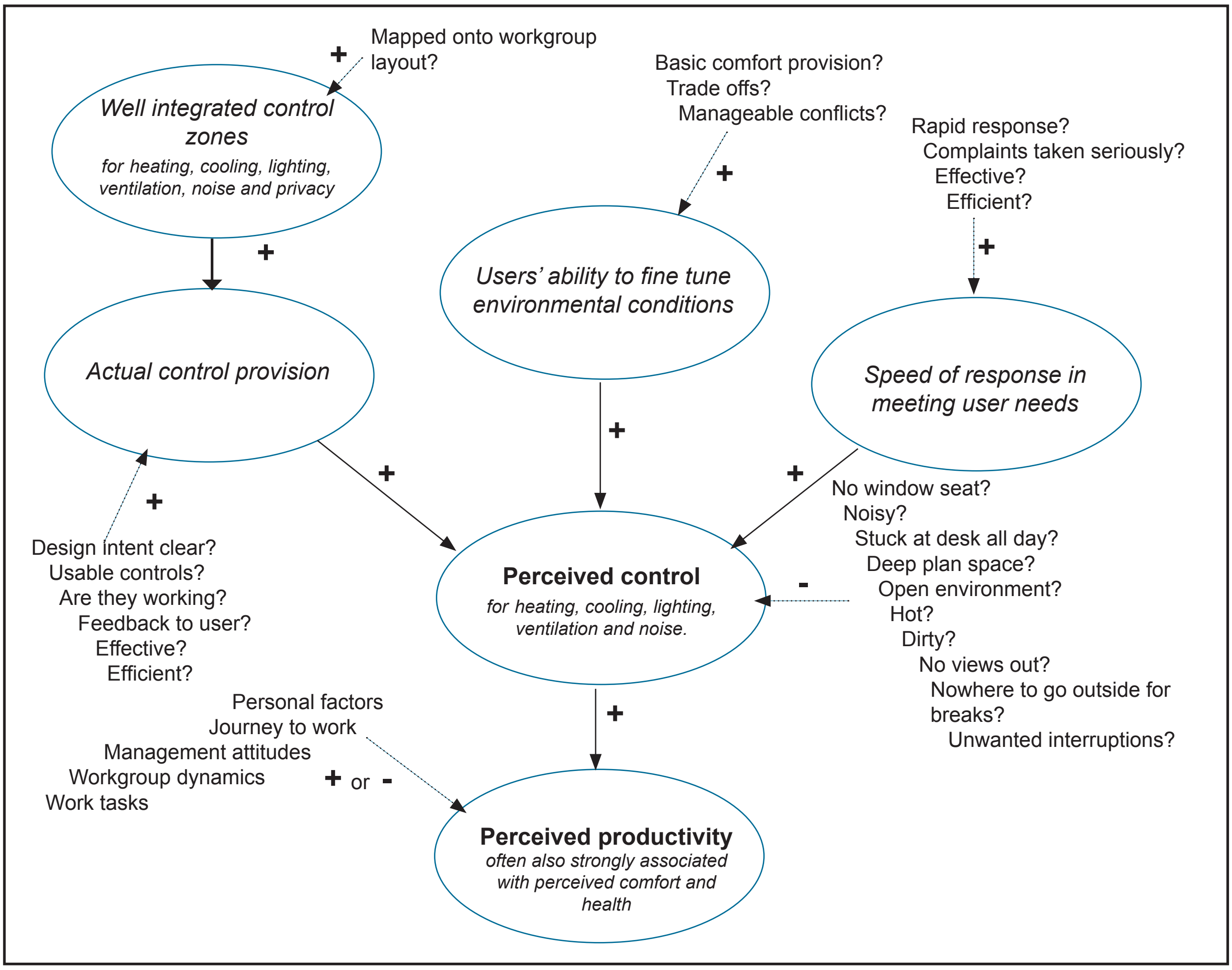
Figure 1: **Perceived productivity question used in Building Use Studies'**

Productivity at work

Please estimate how you think your productivity at work is increased or decreased by the environmental conditions in the building? Please tick one point on the scale

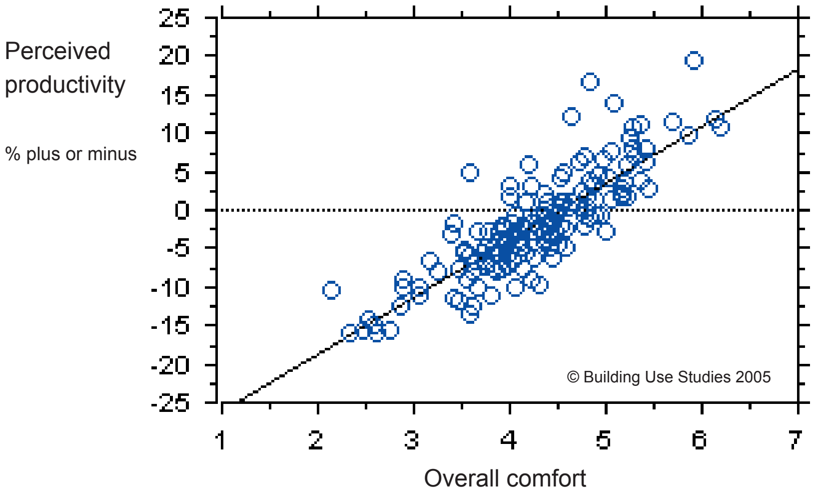
	+40% or more	+30%	+20%	+10%	0	-10%	-20%	-30%	-40% or more	
Productivity Increased by …	1	2	3	4	5	6	7	8	9	Productivity Decreased by …

Figure 2: **Factors affecting perceived control and perceived productivity**



Interpretation: Perceived productivity, comfort and heath are often strongly associated and may even be surrogates for each other. Usually, but there are exceptions, the more occupants perceive that they have some control over their personal environment, the better the ratings for productvity, heath and comfort. Many factors are involved in the wider picture, some with positive effects (+ sign) and some with negative (-).

Figure 3: Perceived comfort and perceived productivity



Interpretation:
This is based on n=151 buildings from Building Use Studies' international dataset for the variables overall comfort and perceived productivity. This is a strong and significant relationship.

r=0.84
r^2=0.7
p=<0.0001

Figure 4: Relationships between control and perceived productivity for office workers in 11 UK buildings surveyed in 1996-97

Building	Type	Average overall percentile	Spearman's Rho (corrected for ties) between mean control and productivity	P value	Significant association between perceived productivity and mean control?
A	AC	52	0.12	0.4133	
B	AC	43	0.17	0.0043	Yes
C	NV	81	0.08	0.4469	
D	NV	12	0.34	0.0348	Yes
E	NV	66	0.30	0.1546	
F	AC	67	0.31	0.0053	Yes
G	MM	91	0.24	0.0425	Yes
H	ANV	43	0.49	0.0002	Yes
I	ANV	22	0.35	0.0033	Yes
J	NV	54	0.16	0.0031	Yes
K	NV	74	0.07	0.6356	

Please also see Figure 3.

Definitions

Buildings: 11 studied by Building Use Studies in 1996-97 for which productivity data are available.

Type: AC=Air conditioned; NV= conventional naturally ventilated; MM=mixed mode; ANV= advanced natural ventilation.

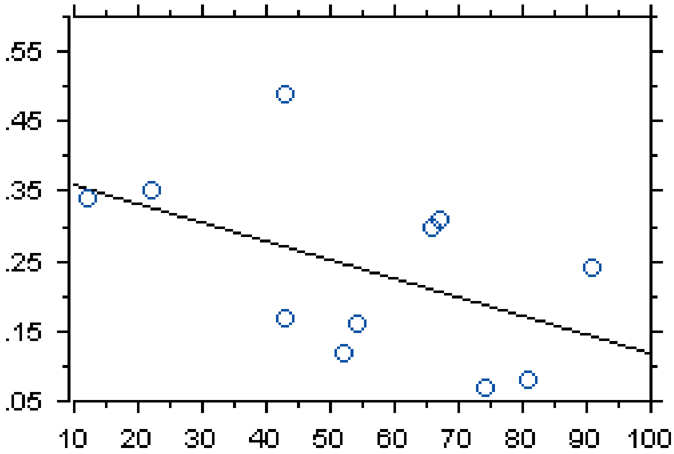
Average overall percentile: Average from percentile score for seven variables from BUS dataset Spearmans'

Rho: Correlation between scores for individual occupants between the mean of five perceived control variables (mean control - heating, cooling, lighting, ventilation, noise) and perceived productivity (see also Figure 1).

P value: P value less then 0.05 indicate a significant association.

Figure 5: **The strength of relationships between perceived control and productivity decline as buildings perform better**

Association (Spearman's rho) between mean control and perceived productivity.



Measure of performance based on average of

Interpretation:
The "average overall percentile" is a measure utilising seven summary variables from the Building Use Studies dataset of 50 buildings. The average percentile score (built from individual percentiles for each of the seven variables) shows how a particular building scores relative to all others. A percentile score of 50 is in the middle of the range. The best buildings
- those with higher percentiles
- tend to have lower correlation coefficients.

Figure 6: **Associations between perceived control and productivity for 11 study buildings and 5 perceived control variables**

	Spearman's Rho (corrected for ties) bew-teen perceived control and productivity	P value	Significant as-sociation?
Heating	0.1	0.0001	Yes
Cooling	0.08	0.0001	Yes
Lighting	0.033	0.2513	
Ventilation	0.06	0.0001	Yes
Noise	0.12	0.0001	Yes

Interpretation:
Giving that perceptions of mean control are related to productivity, which of the five variables making up the mean control statistic are most important? This table shows that noise produces the strongest association with productivity, significant but relatively weak. Heating is the next strongest. Control over lighting is not significant.

The order of these variables tends to confirm earlier work by Building Use Studies which showed that lighting, which is the easiest to change in a building, also is the least effective in its impact!

Figure 7: **Response time question used in Building Use Studies' surveys**

Response to problems

Have you ever made requests for changes to the heating, lighting or ventilation systems?

Yes [1] [2] No — Please give brief details

If yes, how satisfied in general were you with the following …?

Speed of response — Please tick

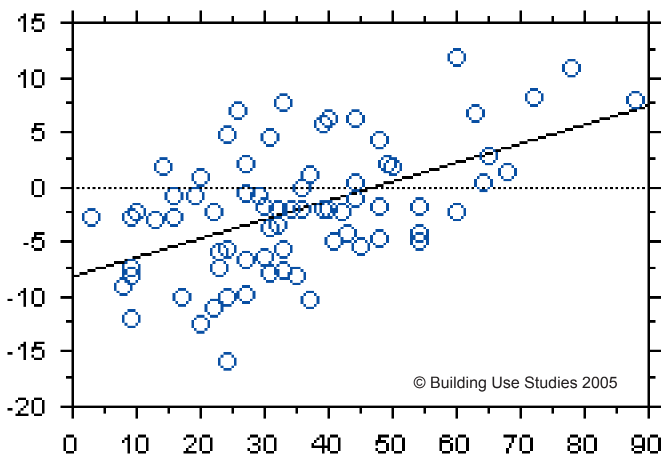
Satisfactory overall [1] [2] [3] [4] [5] [6] [7] Unsatisfactory overall

Effectiveness of Response — Please tick

Satisfactory [1] [2] [3] [4] [5] [6] [7] Unsatisfactory

Figure 8: **Relationship between perceived speed of response in dealing with heating, lighting and ventilation complaints and perceived productivity for UK dataset.**

Perceived productivity
Per cent plus or minus



Speed of response to complaints perceived as satisfactory.
Per cent by building

Speed of response; R^2 = .282; p=<0.001; n=74

Interpretation:
The bottom axis shows the percentage of staff complaining about heating, cooling and ventilation systems who thought that the speed of response by management was satisfactory (a score of 5 or more on a seven-point scale). The vertical axis has the average perceived productivity for all the staff in the building (including those who did not complain).

Perceived productivity and perceived speed of response are significantly associated.

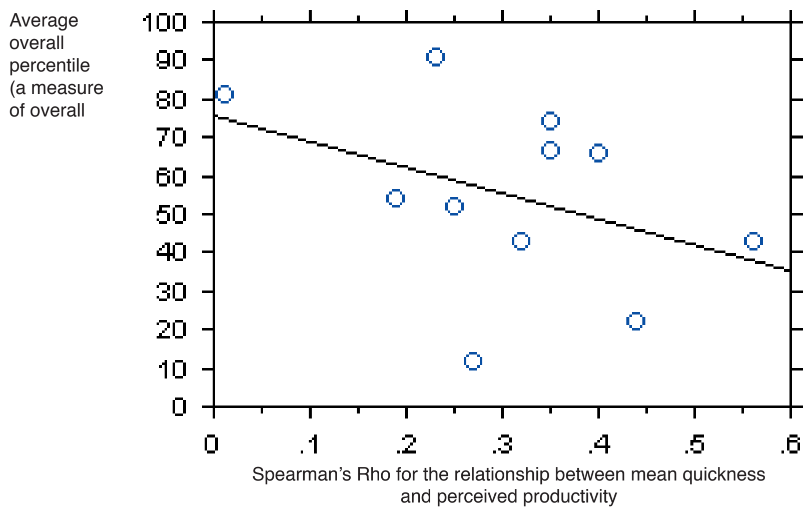
The data are from n=74 buildings, mainly from the UK, in the Building Use Studies 2005 dataset

Figure 9: **Relationships between quickness and perceived productivity for office workers in 11 UK buildings surveyed in 1996-97**

Building	Type	Average overall percen-tile	Spearman's Rho (cor-rected for ties) between mean quick-ness and productivity	P value	Significant association between perceived productiv-ity and mean quickness?
A	AC	52	0.25	0.0433	Yes
B	AC	43	0.32	0.0001	Yes
C	NV	81	0.01	0.9084	
D	NV	12	0.27	0.0961	
E	NV	66	0.4	0.0805	
F	AC	67	0.35	0.0025	Yes
G	MM	91	0.23	0.0274	Yes
H	ANV	43	0.56	0.0001	Yes
I	ANV	22	0.44	0.0004	Yes
J	NV	54	0.19	0.0005	Yes
K	NV	74	0.35	0.0176	Yes

Interpretation:
See Figure 2 for definitions. Column 4 has Spearman's rho for mean quickness and perceived productivity. Mean quickness, like mean control, is a composite variable made up from respondents' perceived view of the "quickness" with which heating, lighting, cooling, ventilation and noise controls meets their needs.

Figure 10: **The relationship between perceived quickness and perceived productivity**



Rho (for this scatter)=-0.42; p=0.1840

Interpretation:
See also Figures 2, 3 and 7. As buildings get better (vertical axis), the relationship between perceived quickness and perceived productivity seemingly weakens. This scatter is approaching significance but is NOT significant.

As the relationship between perceived quickness and productivity gets stronger, overall performance decreases. This implies that quickness of response is more important to users in poorer performing buildings.

Figure 11: Perceived productivity ratings by ventilation type (UK, 2004)

	All	Air condtioned AC	Mixed mode MM	Natural ventilation NV	Advanced natural ventilation ANV
Perceived productivity %	-2.1	-2.4	0.0	-2.5	-2.4
Std. Error	0.8	0.8	2.1	2.4	2.9
Number of buildings	63	32	10	12	6
Worst %	-15.5	-12.4	-11.1	-15.5	-10.0
Best %	10.9	8.0	9.4	10.9	7.7

These are perceived productivity scores for 63 UK buildings from the Building Use Studies dataset split by ventilation type.

Source: Building Use Studies 2005

Figure 12: Overall comfort scores by workgroup surrogates

<table>
<tr><th colspan="2">Correlation coefficient (r) for relationship between overall comfort and proportion of occupants who normally …</th><th>Relationship is …</th><th>Interpretation</th></tr>
<tr><td>Sit alone</td><td>+0.34</td><td>Positive</td><td>Overall comfort ratings go up as the proportion of occupants who sit alone increases …</td></tr>
<tr><td>Sit with one other</td><td>+0.12</td><td>Positive and weak</td><td rowspan="3">… but the relationship weakens as workgroups get bigger until …</td></tr>
<tr><td>Sit with 2-4 others</td><td>+0.05</td><td>Positive and very weak</td></tr>
<tr><td>Sit with 5-8 others</td><td>+0.03</td><td>Positive and very weak</td></tr>
<tr><td>Sit with more than 8 others</td><td>-0.22</td><td>Negative</td><td>Overall comfort goes down as the proportion of occupants who sit with more than 8 others increases.</td></tr>
</table>

Interpretation:
Although we do not collect data on the size of workgroups as such, we do ask building occupants whether they normally sit alone or with others. The results from 100 buildings in our UK dataset show that people are more comfortable when they are by themselves, and less comfortable when with others.