Robert Samuels 1997: Daylight and Productivity
– A Literature Review

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…Natural light or full spectrum light is sometimes referred to as ‘white light’ - being a combination of all the colours of the visual spectrum (including ultra-violet and infra-red); and the sky appears to be ‘blue’ (air molecules scatter blue light more than red). In reality, however, light has no colour - it is *invisible.* We see only its reflection in the environment. It is darkness that we can see…which is why we can’t see *in* the dark.

Preamble

Several constraints on our understanding of the relationship between light and performance arise from this review of published research.

i) Literature evaluating the relationship between *daylight* and productivity is not abundant, and studies relating specifically to productivity in industrial buildings are even more rare. In order to reflect on and illuminate (no puns intended) the issue of light and workplace performance, it is thus necessary to make inferences from research that is more abundant (offices in particular), albeit largely confined to artificial lighting rather than daylighting.

ii) A distinction needs to be drawn between natural daylight (D_{65}) and indoor daylight (ID_{65}). Indoor daylight is ‘attenuated’ *ie* not full spectrum – since glazing absorbs a certain amount of wavelengths. The extent of this attenuation depends on the nature of the glazing. To the degree that indoor daylight varies from natural daylight its efficacy is likely to be compromised. Almost no research has been undertaken on this important element.

iii) ‘IEA Task 21: Daylight in Buildings’ is concerned with advancing daylight technology and daylight-conscious building design; SubTask D is concerned with improving energy efficiency while maintaining the standard of the *visual* and thermal environment. Assessing user acceptability of daylight and satisfaction with lighting controls is a further goal. Daylighting and productivity is not part of the agenda.

iv) A critical distinction is made here between **quantity and quality** (see also ‘synthetic’ diagram in Conclusion). *Quality* here refers to spectral quality, where a high quality of light encompasses either the natural range of wavelengths in daylight or ‘mimics’ this configuration in simulated-daylight or full spectrum artificial lighting. Illuminance, luminance and configuration (or spatial distribution) are here referred to as *quantitative* aspects, affecting visibility and visual comfort. Some authors (Veitch, 1995 eg) use the term ‘quality’ in a generic sense to include everything from performance, communication, mood and health, *and* parameters such as illuminance and luminance. Rather than clarifying the issue this confounds it. Quality is better retained as a referent for spectral wavelength characteristics associated with the colour rendering index (CRI) and correlated colour temperature (CCT).

v) A major factor which seems to have been neglected in many experiments which vary lighting sources and evaluate relative performance and mood is the ‘duration factor’ *ie* the length of time required before a response to light can be expected. Many researchers expose respondents to less than one hour of a lighting condition – while a more profound understanding recognises that exposure over several months, in normal working conditions, and at standard illuminance, would appear to be necessary for this ephemeral energy source to modify the bio-chemical and psycho-somatic internal environment. Spurious conclusions are drawn as a consequence.

vi) Some researchers negate findings of a positive relationship between full spectrum artificial lighting and performance, but they tend to be highly selective in their choice of evidence while ignoring the wide range of other research confirming the interaction. In any event, no claims are made of any negative relationship. If anything, using the relative energy *in*efficiency of full spectrum fluorescent lighting as an argument against their employment in the workplace is superficial, given that technological advances are already countering this and, furthermore, energy management strategies are also available - given that lower illuminance levels of higher quality light are perceived as equivalent to higher levels of lower quality light – up to 25% higher (Aston and Bellchambers 1969; Boyce, 1977; Samuels and Ballinger, 1992).

vii) Virtually all studies that have been carried out regarding the relationship of light (whatever its source) to work output are equivocal and indeterminate - given the large number of other intervening variables which also have an impact on performance in the workplace. Visual as well as *non-visual* variables are part of the same equation. Inevitably, visibility is implicated – virtually all tasks in all walks of life include a visual component which is central to their function. Yet this is but one of many parameters to be considered. There is also a 'photon-neuron' response, and a 'psycho-somatic' response - neurological, hormonal, psychological, motivational, emotional, and experiential factors also influencing the light-performance relationship. Here, non-visual components and those relating to such aspects of a task as decision-making or other cognitive requirements complicate the light-performance relationship. Specifically, this wide variety of psychological and physical factors that affect workplace satisfaction and performance range from neuro-endocrinal equilibrium, levels of physiological arousal and attentiveness, through sense of responsibility, motivation/incentive and level of participation and/or control, to sensory inputs related to space, light, heat and sound, and the purely physical and mechanical requirements of tasks and equipment including requisite safety and ergonomic provisions. This 'multi-dimensional' aspect makes it difficult in the extreme to draw conclusions about the influence of light on productivity. Uncertainty also surrounds the measurement of intangible elements such as arousal, distraction, mood, fatigue and motivation. Even the effects of lighting on visual fatigue are difficult to assess (Megaw, 1990).

Ultimately, however, even if enhanced lighting levels or superior quality tend to increase morale rather than having a direct physical effect, the investment is surely still worthwhile. To wit: recorded increases in productivity in a range of American industrial buildings where lighting levels and visual acuity were increased (amongst other complementary influences) average around 15%, which in any consideration must be profitable (Romm & Browning, 1994) – irrespective of whether or not the lighting changes are a catalyst for non-visual or visual transformations.

viii) Given that 80-90% of the lifecycle cost of running industrial or commercial buildings is for salaries, and that productivity inevitably must be related to worker satisfaction and well-being, designing for energy efficiency should not ignore human needs and preferences (Ne'eman and Selkowitz, 1984a).

ix) All things considered, inferences drawn from this literature review strongly suggest that *there* ***is*** *sufficient experimental and experiential research and evidence to endorse the use of daylighting and full spectrum daylight-simulating lighting to enhance performance in the workplace.*

1 Introduction and General Theoretical Considerations

1.1 Neuro-endocrine and 'photo-somatic' interactions with light

Fundamental to the discussion which follows is the recognition of the neuro-endocrine response of humans to the environment. This is both a 'psycho-somatic' response and a bio-chemical response: any interaction with the environment – physical, social or emotional - prompts an associated internal interaction between the hypothamalus, pituitary, adrenals etc, whether the stimulus is experienced as negative or positive. Stress responses (and their consequences), for instance: cortico-steriod and adrenalin secretions, are now well recognised.[1] Less well recognised is the human response to light *ie* the non-visual response – where light acts as a potent form of energy, having

[1] See Samuels (1978), *The Psychology of Stress: The Impact of the Urban Environment,* Unpublished doctoral thesis, University of Reading, UK.

profound impacts on human well-being both physical and psychological, and thus potentially on performance and productivity.
The hypothalamus is intimately involved in this ‘photon-neuron’ response. It is connected via a separate nerve pathway from the retina, from which impulses travel to the suprachiasmatic nuclei which serve as a vital component of the internal biological clock, timing the 24^{hr} (circadian) cycles of physiology, behaviour and biochemistry. The photo-sensitive (neuro-endocrine) pineal gland is also associated with light/dark cycles, and secretes the hormone melatonin in the dark, which conditions arousal and sleep. Where people are exposed to light, either natural or, if artificial, bright (2500 lux) or daylight-simulating (full spectrum light or FSL), melatonin secretion is properly managed; where light levels are low or the visual spectrum is attentuated or incomplete, melatonin continues to be secreted (unnaturally). Standard levels of indoor lighting (400 or 500 lux, for instance, is equivalent to ‘biological darkness’ – Lewy *et al* (1980), Brainard et al, (1988).

Lighting engineers and architects use levels of lighting which are adequate for vision and for aesthetic purposes, but not for biological stimulation. Moreover, energy efficiency goals frequently result in either lower levels of illumination or the use of lamps which are not daylight-simulating. The consequence of either or both of the above, ultimately, can manifest as depression of the nervous system, low arousal, and emotional depression; and/or the so called ‘winter-blues’ - which mood-state is now known to be associated with light deprivation. Further important consequences are a drop in attentiveness, or an increase in distraction or inattentiveness (see Samuels *et al,* 1996 for review). A depressed mood-state, coupled with a state of low arousal, and a disharmonious/ill-balanced biological clock and psycho-somatic state – where fatigue, lethargy and headaches are more prevalent, not surprisingly, are likely to result in a fall-off in performance, and ultimately a drop in productivity. The cost of a single day of lost productivity (due to accident, absenteeism, or fatigue…) is equivalent to the energy costs of lighting a workplace for an extensive period, but this comparative costing is rarely if ever undertaken.

- *light therapy*

Further evidence of the salience of light to well-being derives from the manifest success which light-therapy has with people suffering so-called 'SAD' (seasonal affective disorder) symptoms, due to light deprivation, particularly in the winter months, particularly in the northern hemisphere. An immediate positive response to exposure to bright *and especially FSL* (Lewy *et al*, 1980, Rosenthal *et al*, 1984, Brainard et al, 1990) bears witness to the reality of light as bio-energy.

1.2 Light and performance

1.2.1. Visual inputs

Lighting can directly affect visual performance and thus productivity in two interrelated ways: by directly changing the physical characteristics of the task itself (glare, flicker, etc), and/or of the visual system (acuity). Degree of visibility is the crux here. Visibility is the principal criterion by which illuminance recommendations and standards are defined (IES Lighting Handbook (Rea, 1993).

- *visual acuity*

By definition, where increased effort is required to complete a visual task due to poor and/or low levels of lighting, both eye fatigue and general fatigue are more likely, with a corresponding fall off in performance and productivity. Implicated here, in particular, are glare, veiling reflections and flicker. Furthermore, colour rendering capacity of a light source and colours in the surrounding space modify visual effectiveness; and dark colours absorb light whereas light colours reflect it (Vischer, 1989).

Also, generally, older people benefit more from improved lighting because their own visual apparatus degenerates naturally with age (Boyce, 1972; Sundstrom, 1986). Given the ageing of populations world-wide, this is a consideration of importance with regard to maintaining and enhancing productivity in the work force in the next century.

1.2.2. Non-Visual inputs

Indirectly, non-visually, lighting can affect the neuro-endocrine system, thus impacting on arousal, concentration and attentiveness, effort and fatigue, energy states (from hyperactivity through feeling energetic to feeling lethargic), headache, and mood, motivation and satisfaction.

As with illuminance, arousal increases directly as stimulation from the environment increases, but performance falls off when stress levels are reached, obviously different for each individual.

Uniform, dull, constant lighting is likely to decrease arousal (Boyce, 1981). Daylight, with its inherent variability, should thus enhance arousal. Ne'eman and Selkowitz (1984a) mention 'recent indications of the variable nature of daylighting being physiologically and psychologically beneficial'.

The spectral distribution of daylight depends on whether this light comes from skylight or sunlight; and there are even differences depending on whether it enters a building from the north or the south (Lynes *et al*, 1966). In the southern hemisphere, for instance, daylight from the north is warmer and from the south cooler (bluer). Here too atria and skylights admit northern light and direct sunshine. Ne'eman and Selkowitz (1984a) believe that where sunlight can be admitted without causing glare or overheating 'it brightens the building, thus contributing to the well-being of its occupants'.

- *mood, arousal, attention, motivation*

Mood can influence performance, but whether mood is affected by visual appearance is less obvious, since many other factors intervene too – including habituation to a novel situation, where original stimulation can become neutralised over time. Veicht and Newsham's (1995) synthesis suggests that improvements in performance with increasing illumination might be transitory. Moreover, different individuals react differently to the same set of stimuli – depending on their past experiences, genetic make-up, status positions, expectations and age, *inter alia*.

A host of field studies have indicated that light quantity (Kripke et al, 1994) and quality can influence mood. There is a generic characteristic of humans that seems to be independent of culture and climate, intention and task: *daylight* is preferred to artificial lighting (Collins, 1975; LBL @ www#4). This preference has been shown to be the case in offices (Wells, 1965; Marcus, 1967; Ne'eman, 1974; Cuttle, 1983; Wotton and Barkow, 1983); in hospitals (Hopkinson, 1964; Wotton, 1986) and in homes (Bitter and van Ierland, 1967; Hopkinson, 1967; Ne'eman, 1974). *However, none of these studies correlated daylight preference with productivity.*

Instinctively we should expect there to be a natural, organic response to natural prevailing conditions (daylight is obviously the best light for colour rendition, varies naturally, and is the natural evolutionary environment of human beings). Consequent to this, it can be further expected that where people feel satisfied and 'in tune' with nature they are likely to work better. *Sun*light, however, is more problematic since it is associated inevitably with temperature and thermal comfort, and indoor sunlight can often be distracting and uncomfortable visually. Moreover, direct sunlight can interact with volatile organic compounds (VOCs) that might be emitted by off-gassing of other products, thus forming a type of indoor photochemical pollution normally associated with urban air pollution or smog.

1.3 Daylight and Artificial Light

The international daylight standard D_{65} corresponds to clear northern sky conditions (temperature of 6500K). Daylight-simulating artificial light is thus in the temperature range of 5000 to 6500K, which is cool and blue. With regard to buildings (and their occupants) the major component of natural light for consideration is skylight not sunlight.

The wavelength spectrum of natural light from the sun is broad, and has no large peaks. At different times of the day, and at different altitudes and latitudes, and at different seasons, the relative amount of energy at each wavelength changes. There is, thus, no one daylight spectrum. Dusk, for instance, is predominated by the long wavelength red-end of the spectrum.

Given these many factors which impact on this 'daylight factor'[2], including air pollution and clouds, and distance from a window, daylight tends to be variable and changeable, particularly when compared to artificial lighting which is constant. This variability (the 'living' quality of daylight) is said to be one of the major reasons why people (subconsciously) prefer daylight to artificial light. Contact with natural conditions, via a window, is also extremely important psychologically; and daylit interiors are evaluated as more pleasing, are said to increase detail and appearance of objects and also to have a different 'feel' (Collins, 1975). Sundstrom (1986) cites research by Wells in 1965 among 2500 office employees where 89% would prefer to have daylight penetrate into the interior of their office space. Also cited is work by Sommer in 1974, where occupants of windowless offices would have preferred daylight. Bio-chemically, absorption of full spectrum natural light is now also know to be fundamental to health and performance (see Samuels *et al*, 1996 for review).

[2] technically, daylight factor is the % of available light than illuminates an interior space. Simple to moderate tasks require a daylight factor of 1.5 to 4.0

- *attenuated indoor light*

Indoor daylight is *attenuated ie* not full spectrum light, since glass does not transmit the full spectrum of daylight. UVR is largely blocked, and even 3mm clear glass permits only 86% visible spectral transmission. The importance of this realisation is that indoor daylight will not have the full psycho-biological benefits of outdoor daylight. Only 25%, for example, is transmitted through 13mm bronze plate glass (ASHRAE, 1989) - frequently used on high rise office towers. The glazing currently favoured by Pilkington (Australia) is Suncool™ laminate SL20 Green, which transmits 17% of the visible spectrum. It is said that glass that transmits more than 55% of visible light provides an accurate *perception* of daylight conditions (Sect 5.11.5 in BC-EST FSCI Environmental Report; see: www#5), albeit still biologically inappropriate.

Clarke (1979) showed these transmittance differences occurring largely in the red and *particularly in the blue* extremes of the spectrum for 6mm of clear float glass, and called the result : interior daylight, or ID_{65}. In other words, CIE D_{65} is not equivalent to the daylight experienced indoors, which is why it is here described as ‘attenuated’.

Kok et al (1985) measured the spectral irradiance inside a room, both with and without fluorescent lighting and also with the windows open or closed. They noted higher UV content when the windows were open, while the impact of closing the windows was quite obvious. Despite having the fluorescent lights on, there was still a noticeable reduction in spectral irradiance compared to when no lights were on but the windows were open.

Kok and Hengstberger’s (1991) measurements of interior daylight showed that a number of factors - additional to the absorptance of window glass, *ie* solar angle, cloud cover, atmospheric ozone and aerosol content – also have a marked influence on spectral properties. Furthermore, most building and furniture materials have a low ultraviolet and blue reflectance (*ie* tend to absorb UVR and blue), which results in a significant lowering of the correlated colour temperature (away from the 6500K of D_{65}) towards the warmer, redder end of the spectrum.

> Given that both glass and materials absorb UV wavelengths, interior daylight is particularly deficient at the shortened wavelengths, the very wavelengths which have a powerful actinic or chemical effect - and thus psychobiological effect.

- *exposure to artificial light and the neuro-endocrine response*

Typical levels of 'standard' indoor fluorescent lighting (cool-white tubes emitting 500 lux at desk-level, for example) have had no impact on melatonin secretion (Lewy *et al*, 1980, Brainard *et al* 1988), while 'bright' light exposure does (Lewy et al, 1980), but it is impractical, inefficient and uncomfortable to work under 2500 lux. Full spectrum artificial lighting includes 'near' ultra-violet light (UVA) in daylight proportions, on the other hand, seems able to perform this function even at standard illumination levels ***over a period of time.***

- *duration vs. intensity*

Experimental studies that bring subjects into an artificial environment for brief periods of time are naïve in the extreme (see, for example the recent research by: Boray et al, 1989; Veitch et al, 1991;Baron et al, 1992).

This fundamental flaw in procedure is both surprising and alarming, since spurious inferences are made as a consequence. Researchers should have understood that the influence of light on core neuro-endocrine functions, particularly at standard illumination levels, is not instantaneous. Even exposure to bright light of 2500 lux requires several hours to get a sustained response. Lewy *et al* (1980) reported that melatonin concentrations begin to diminish after about 20 minutes of exposure @2500 lux, and reached daytime levels after about an hour; but @500 lux exposure there were no noticeable differences in concentration levels. It should not be expected that low levels of indoor light for brief periods should have any effect on diurnal patterns of melatonin secretion or suppression.

To expect people to walk into a laboratory with full spectrum lighting and immediately start performing better, to display a sudden enhancement in attentiveness, is surely an indication of a serious lack in understanding of the theoretical basis of the relationship between light and performance. Where influential researchers make recommendations based on flawed premises this is of serious concern.

Boray and colleagues (1989) report, for instance, that after *35 minutes* no significant differences were found among three lighting types (warm-white, cool-white and full spectrum) with regard to simple tasks like underlining nouns and subtracting numbers (meaningless tasks in reality).
Recommendations not to install fulls spectrum lights were made.

Veitch et al (1991) exposed their respondents to test conditions for 45 minutes, during which time they undertook separate tasks lasting 2, 5 and 15 minutes. Besides their superficial rejection of the potential full spectrum effect – by selecting a few studies which reject the hypothesis and ignoring the vast literature on positive effects[3] – this study introduced the notion of the 'demand characteristic' where respondents were told to expect either better *or* worse performance under FSL lamps, yet produced better performance in both cases. This appears to be a return to the Hawthorne effect, and seems to prove

[3] They fail to mention even the classic research in the field undertaken by Wurtman, Hollwich, Ott, *etc*. Samuels *et al* (1996) cite over 100 research reports confirming the relationship between full spectrum light and performance, mood, health.

nothing, despite the claims of the authors that it disproves the FSL effect. They do mention the ‘short exposure time’, but this does not appear to affect their evaluation of the validity of their results. Sophisticated statistical analyses are undertaken, but the basic premise remains flawed.

Baron *et al* (1992) found no effects of luminous conditions on mood and performance. The exposure time for subjects was not stated, yet can be inferred from the description of the tasks set to be about *20-40 minutes*. Knez (1995), who criticises this work on this dimension himself fails to state the duration of his own experiment – although he does reports some positive findings relating to cognitive performance via enhanced mood.

The research on full spectrum lighting of Ott (1982), Hughes (1983); Erikson and Kuller (1983); Rosenthal *et al* (1984); Wohlfarth (1986), Lindsten and Kuller (1987), Samuels and Ballinger (1992), and other research related to circadian rhythms, biological clock, SAD and phototherapy (see Wurtman *et al*, 1985 for general review) all appreciate the reality of the ‘photon-neuron’ relationship, and project their studies over considerable periods of time. Lindsten and Kuller’s work with school children was over a one-year period, Wohlfarth’s over a 10 month period, Ott’s over a two-month period; while Erikson and Kuller’s research in an office was conducted over a 6 month period, and Samuels and Ballinger’s over an 8 month period. A study to be undertaken during 1998 on the potential impact of full spectrum lighting on performance and mood at school, for the NSW Public Works Dept/Education Research, will be conducted over a full year (Samuels, forthcoming).

Rosenthal’s work, over 7 days, indicated significant mood changes with bright light treatment but not with dim light. Close examination of these results indicates a clear rise in positive effect from day 1 to 5 and then a levelling out under the bright light condition, while in the dim light condition there was a slow yet sustained increase after day 4, and a slower decline after treatment was withdrawn after day 7, with a final state at a higher level than that to which the bright light group dropped after withdrawal. This again appears to support the 'duration rather than intensity' hypothesis.

- *efficiency and FSL*

Studies also show that higher quality light is perceived as being equivalent to poorer quality light at higher levels of illumination. This suggests that full spectrum lamps, relatively inefficient as they are, can be employed efficiently by using less lamps per area (and by supplementing the luminaires with reflectors). Moreover, Vitalite©, the internationally best known full spectrum lamp company now produces a lamp which emits 25% more light than older models, again enhancing the possibility of intelligent energy management resulting in energy consumption savings (www#2).

The above synopsis is based on literature analysis inclusive of:
Plant, (1970); Milova, (1971); Birren, (1972a, b, c); Rowlands *et al* (1973); Maas *et al* (1974a,b); Greiter *et al* (1979); Hollwich & Dieckhues (1980); Ott, (1982); Hughes, (1983); Wurtman *et al* (1985); Mahnke & Mahnke (1987); Samuels & Ballinger (1992); Samuels (1994); Downing (1996). Samuels *et al* (1996) undertook a study for the NSW Dept of Public Works/Education Section which comprehensively evaluated the literature on this issue.

2 Field Studies:- Light in Buildings and Work Performance

2.1 Task Illumination and Visual Efficiency - or Motivation?

In a generic sense, it would appear to be self-evident that where light is insufficient to adequately perform a task (distinguish details, discriminate colours…) *ie* where visual difficulty is increased, performance is likely to decrease, albeit not a linear relationship. At the other end of the continuum, one principle seems to be accepted throughout the literature: the recognition of the law of diminishing returns, or a saturation effect. This grew from Weston's early work in the 30's and 40's with regard to the relation between increasing illumination and increasing visual efficiency.

The best known early work on illumination and productivity, and which is still influential today, was that carried out by Mayo at the Western Electric Company at Hawthorne, Chicago, and which has become known for unearthing the so-called 'Hawthorne Effect' (see Urwick and Brech (1965) for review).

Increased and decreased lighting levels both resulted in increased productivity. Similarly, even productivity of the control group increased (where illumination was not modified at all). It was concluded that management showing interest had motivated workers to subconsciously work better, for whatever reason (more cooperative relationship, greater identification by workers with management goals etc), not the level of light *per se*. Also rivalry between the two groups could have had an added effect.

A further series of early investigations concerned with *daylight* illuminance and industrial output were conducted by Elton (1920) [silk weaving] and Weston, (1922) [linen weaving]. The amount of daylight outdoors during a *15 week* period was clearly related to output in silk weaving. Similarly, output of linen weaving declined as the amount of daylight inside the weaving shed declined. Possible impacts on motivation were not discussed.

Luckiesh and Moss (1931)[4] reported changes in work output as a result of considerable illumination increases [from three-fold to ten-fold increases), ranging from 4% to 13%, for a variety of industrial tasks: metal-bearing manufacturing (15%), steel machinery (10%), carburettor assembly (12%), iron manufacturing (12%). The increased productivity did <u>not</u> correlate directly (*ie*

[4] Also summarised by McCormick (1970).

in strict linear fashion) with the quantity of extra illumination. Task-specifics seem to intervene. Again, too, the impact of other simultaneous changes, including to the psychological atmosphere, cannot be discounted.

Another study (General Electric, 1953) reported a 32% decrease in the accident rate in a heavy-manufacturing company after implementation of an illumination improvement plan. Here illumination was increased four-fold. Again, extraneous influences cannot be discounted.

Stenzel (1962), measured the output from a leather factory, *over 4 years*. Initially lighting was provided by *daylight* supplemented by fluorescent lamps, giving an overall illuminance of 350 lux. Then the daylight was virtually removed and a uniform 1,000 lux was provided by fluorescents. Here statistically improved performance was related to the higher illumination, irrespective of its source. However, the latter condition did more than just increase lighting: it also changed the colour and the distribution of the light; and motivational factors during this research period are an unknown factor.

There are yet other endemic problems associated with changes in lighting. Such changes are frequently accompanied by changes in temperature; or a move to a new building, new working arrangements, even new machinery (Pilkington's Hobart factory being a case in point[5]) – which confounds the relationship between light and work.

Studies by IERI (1975), Hughes and McNellis (1978), Barnaby (1980), Katzev, (1992) and Odemis, (1997) all show some improvement in productivity in office environments with increases in illumination; but it is unclear how much of that change can be attributed to visual acuity and how much is related to motivational factors. Barnaby, for instance, showed how errors performing insurance office tasks decreased by up to 45% for a three-fold increase in

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[5] see Samuels (1997): Production Savings through Daylight Glazing: Hobart Study [Internal Report to Pilkington (Australia)]. The substantial amount of daylight admitted by the loading

lighting, accompanied by an 8% increase in productivity. Worker satisfaction simultaneously increases in proportion to the level of illumination, while the salience of a satisfied workforce is incalculable. Hughes and McNellis found that clerical workers (involving a visual search task) had an average gain in productivity of 5% and 9% when lighting was increased two-fold and three-fold, respectively. Again higher lighting levels were evaluated as being more desirable, and older staff found the higher levels more acceptable – yet another factor.

Improvements in performance are greater for visually demanding tasks, especially those performed by older workers. Similarly, but inversely, an OAA (1984) study showed that by reducing lighting, in order to save energy, employees began complaining of headaches and eyestrain, and productivity declined by 30%. Again, negative motivational factors must be acknowledged.

Wineman (1982) showed how worker satisfaction is associated with job performance, and that lighting (visibility) is considered to be one of the most important aspects of a work environment. *Daylighting* and view were also perceived as important factors influencing satisfaction in office environments. Other research suggests that workers desire *daylighting* independent of its contribution to task visibility (Ne'eman et al, 1984). Where *sun*light admission is concerned both heat-gain and glare are associated with it, complicating possible impacts on performance. Task-specifics will also play a role here.

Ne'eman *et al* (1984) surveyed workers in an office building with wings around three sides of an internal light-well atrium enclosed by a glass skylight, and high windows and narrow section allowing *daylight* to penetrate deep into the interior. Illuminance levels averaged 550 lux. More than 90% of workers (mostly a female sample) indicated that amount and quality of light for reading and writing were very important, as did a further high percentage with regard to computing, filing and other tasks. Correlation statistics indicated that features

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doors further confounds any relationship between extent of glazing and the productivity increases measured in the new building.

deemed to be most important and most satisfactory included amount and quality of light for reading, writing and other tasks. These results appear to endorse the daylight 'factor' built into the design, although no questions directly referred to daylight per se. Interestingly, dissatisfaction was highest with thermal comfort year round: overheating occurred even in winter. No attempt was made to correlate this with the (large) extent of natural light (sun, sky or daylight) entering the building.

Interesting research by Nelson *et al* (1984) showed a significant interaction between temperature and illuminance in relation to feelings of sadness and bad mood, which were highest with combinations of 300lux @ 13^0C (low visibility and cold) and 100lux @ 30^0C (poor visibility and hot).

Wotton and Barkow (1983) evaluated 6 office buildings but found no significant relationship between either daylight and work productivity - as measured by number of coffee breaks and trips to the bathroom, etc - or % glazing and physical well-being, although workers in situations with less glazing (11% as opposed to 68% of wall) suffered less headaches but also more eyestrain/glare –suggesting that a balance is required.[6] Measuring performance by trips to the washroom and coffee breaks - so-called 'non-productive' activities - is hardly a robust measure of the opposite: productive activities, and by trivialising the issue this research cannot claim to have found or not found a daylight-productivity relationship.

- *views*

Ne'eman *et al* (1984) also concluded that the more limited the views from windows (surrounding high rise buildings, *eg*) the less important they appear to be for worker satisfaction. Research on the affects of views-of-nature on attention seem to consistently endorse this as beneficial. For instance, a natural

[6] Daylight penetration into a building is inevitably accompanied by solar/heat gain. The % glazing required to optimise the benefits of daylight as opposed to its costs (cooling energy or glare) is not the subject of this review.

view as opposed to a view of the built environment has been associated with positive physical and mental health effects when people are confined (in prisons, for eg: Moore, 1981) or sick (Ulrich, 1984; Verderber and Reuman, 1987). Tennessen and Cimprich (1995) undertook field research with students in dormitories and also found that natural views from windows were associated with better performance on attentional measures. Kaplan and Kaplan (1989) determined four factors which underlie this attention-directing capacity of natural views: fascination or involuntary attention, sense of relief or escape, immersion, and compatibility.

Hartleb Puleo and Leslie (1991) found that the presence or absence of a window seemed to have no significant effect on performance on a cognitive test. Moreover, although the window was initially a distracting feature there was a beneficial effect when longer periods of work were concerned.

2.2 Spectral Quality

Maas et al (1974), Hughes (1980), Ott (1982), Erikson and Kuller (1983) and have conducted field experiments where full spectrum lighting has resulted in fewer vision problems, less visual fatigue, enhanced alertness, improved performance, less lethargy, diminished hyperactivity. Hollwich and Dieckhues (1968) and Lindsten and Kuller (cited in Kuller, 1987) measured increased cortisol (a stress hormone) in spectrally unbalanced artificial light and in the absence of daylight, respectively.[7]

The Westpac field study (Samuels and Ballinger, 1992), similarly, showed that high full spectrum lamps were perceived as being more satisfactory on several visual dimensions than lamps of lower quality but higher illuminance. People also felt more energetic and less lethargic to a significant extent, and experienced significantly less headaches.

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[7] see Samuels *et al*, (1996) for a full review [available in Open Reserve, UNSW Library].

3 Laboratory Experiments: Illuminance and Productivity

An analytical approach (for visual tasks at least) was devised by Weston (1945) and called the Landolt ring chart. It consists of a series of C shapes with the gaps oriented in different directions. The time taken to specify a particular direction under different lighting conditions thus offers a relatively objective measure. The effect of increasing illumination follows the law of diminishing returns *ie* increases in illumination lead to smaller and smaller changes in visual performance until saturation occurs. Again, where the task is relatively more difficult (smaller size rings) the higher is the illuminance at which the saturation occurs.

Lion et al (1968) used two inspection tasks to test differences between incandescent and fluorescent lighting, both @320 lux. Fluorescent conditions resulted in the better performance, but only for one of the two tasks. The researchers considered it unlikely that the spectral differences of the lighting were the cause, rather than other factors such as shadowing and specular reflections. Again. it is difficult to generalise, given the importance of detailed differences in task requirements, age factors, background factors, motivation, practice, and spectral quality differences.

Stenzel and Sommer (1969) varied illuminances on two tasks. An increase in illumination from 100 lux to 1700 lux resulted in an increase in performance, in one case; in another, performance fell off after 700 lux (but small numbers and the influence of one individual confound this result).

Probably the most influential investigations into the effects of lighting on appearance and acceptability were by Flynn *et al* (1973; 1979). Participants in this research rated the appearance of a conference room lit in a variety of ways in terms of visual clarity, spaciousness, pleasantness etc. Lighting conditions were varied in uniformity, brightness and distribution ie overhead and/or peripheral. Considerable selectivity in visual experience was displayed *ie* a search for meaningful information influenced preferences. Preferences were expressed for combination overhead and wall lighting, experienced as enhancing spaciousness and perceptual clarity. This has fortuitous implications for daylighting, which by nature illuminates walls, surfaces and even ceilings. Flynn's (1977) and Baron *et al* (1992) research which reported that subjects prefer dim to bright light, and warm to cool light were later challenged by Knez (1995), who points out that these studies did not control for CRI *ie* light quality as here defined.

Smith and Rea (1979) showed an increase in performance (checking numbers) with increasing illumination, but here the performance of older subjects was worse than that for younger subjects, which is the inverse of that expected.

Boyce (1981) summarised the many results derived from the so-called Visibility Approach as the following: 'relative task performance depends more on intrinsic difficulty than on task illuminance'.

Gifford *et al* (in press) re-examined experimental evidence concerning the hypothesis that increasing illumination improves task performance, and concluded that there *is* a relationship, albeit not extensive; and that adaptation seems to negate the effect over time. In other words, the increase might well be transitory, and people habituate to conditions that are no longer novel.

- *flicker*

Wilkins *et al* (1989) showed how flicker from fluorescent lamps produces eye strain and headache, and that the incidence of both was reduced by about half when high-frequency or electronic ballasts were substituted. Veitch and McColl (in press) found that visual performance was improved under 20kHz modulation in comparison to 120 kHz under fluorescent lighting, confirming Wilkins (1986) earlier work.

3.1 Spectral Quality

Experiments have shown a marked reduction in errors made in a colour sorting tasks as the CRI increases. For instance, most errors occur under high pressure sodium lamps and fewest under full spectrum lamps (British Standards Institution, 1967 & 68). Similar results were found in studies in hospitals – the higher the CRI the better the light source for making colour judgements (joint Committee on Lighting and Vision, 1965). There is a further relationship between CRI (light quality) and neuro-endocrine responses which was not yet appreciated at the time of these experiments.

Experiments involving colour discrimination indicate that unless colours are at the extremes of the spectrum, an illuminance of about 300 lux is sufficient for good colour judgement (Cornu & Harlay, 1969). The effect of illuminance is thus much less than the marked differences between colour discrimination when light sources have different spectral emissions.

Lynes (1973) claims that tinted glass in windows can transmit a CRI superior to that of standard fluorescent lamps, although no further research on this interesting aspect has been reported. This would suggest that colour discrimination reliant on windows and daylight is not likely to be negatively affected by the presence of tints in windows, albeit that a proportion of the UVR is absorbed by the glass – which potential psycho-biological impact was presumably not appreciated by the researcher at the time.

Rowlands et al (1973) evaluated the effects of different fluorescent lamps with different spectral emissions, and found no difference where the task was achromatic (no colour). This was confirmed by other research (Smith and Rea, 1979); and anticipated by Milova (1971). Colour tasks produced variable results, resulting in no clear relationship being established. The duration of these tests is not apparent.

Boyce and Simons (1977) found a reasonable correlation between accuracy of performance and colour fidelity or colour rendering. Lamps designed for accurate colour judgement (daylight-simulating) produced the lowest error scores, while the high pressure sodium discharge lamp - designed for efficiency - gave the worst scores. Collins and Worthey (1985) confirmed the unsuitability of these lamps for work requiring colour judgement (see also: British Standards Institution, 1967 & 68).

Altman (1977) showed that lights of equal luminance but different colour could have very different perceived brightness. The interaction between colour-rendering properties and illuminance has been investigated in several studies (Aston and Bellchambers, 1969; Bellchambers and Godby, 1972; Boyce, 1977 *inter alia*). Together they support the conclusion that at low illuminance there is a preference for lamps with high colour rendering properties – possibly because they produce greater saturation in surface colours and therefore give the environment greater visual clarity (Megaw, 1992).

In general, brightly coloured surfaces in the vicinity of a task are likely to interfere with the colour rendering characteristics of the primary light source, be it daylight or artificial.

- *spectral power distribution*

Berman (1992) has theorised that the use of fluorescent lamps with peak output around 508 nm, where ‘scotopic sensitivity’ peaks (which he calls scotopically-enriched light) – that capacity to see as light falls), reduces pupil size, in comparison to equal levels of other light sources. Smaller pupils increase depth of field. Applying the hypothesis in laboratory studies, pupil size reductions with scotopically-enriched light were associated with better performance on a challenging visual performance task (Berman *et al*, 1993, 1994).

In other words, Berman found that reduced light levels may not cause any changes in visual potential and may, in some cases, actually improve vision if the new light spectrum has increased portions of *bluish greens...the* 'scotopically richer spectral content'.

Table 1:

Scotopic/Photopic Ratio (S/P)	
warm white fluorescent	1.0
incandescent	1.41
cool white fluorescent	1.46
trisphosphor (4000K) fluorescent	1.62
daylight-simulating fluorescent	2.22
sun (CIE_{55} illuminant)	2.28
sun and sky (CIE $_{65}$ illuminant)	2.47

Adapted from: Berman (1992)

> Evidence now suggests that there is a complex interactional synergy between illuminance and lamp spectral power distribution with regard to cognitive task performance and social behaviours (Baron, Rea, & Daniels 1992). Visual acuity pales in comparison.

4 Recent Reports of Fortuitous Productivity Increases in Buildings Designed to be Energy Efficient

A synthesis by Romm and Browning (1994)[8] documents 7 cases in the USA (and 1 in the Netherlands) of both office and industrial buildings (both new and retro-fitted) in which efficient *lighting, heating and cooling, and/or daylighting* are said to have 'measurably increased worker productivity, decreased absenteeism, and improved the quality of work performed'…and…'increased work quality by reducing errors and manufacturing defects'.

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[8] document supplied by Brett Woods of Pilkington, Victoria.

At first reading this is enormously encouraging. These increases are attributed largely to enhanced visibility: the capacity to detect errors etc. In several of the cases cited, however, *more than lighting* is involved in these increases in productivity, confounding the simple linear relationships hoped for[9]. Furthermore, the impact of morale boosting as a result of the lighting upgrades cannot be calculated. If, nonetheless, in the worst-case scenario, this morale-boost is almost completely responsible for the productivity increases and not the lighting *per se*, it is still worth it to up-grade given the substantial productivity increases apparent.

Only the case of the Wal-Mart store seems unequivocally to implicate *daylight* and performance, and this fortuitously and by sheer serendipity – although none the less relevantly.

- The Reno Post Office: lighting was improved ('more efficient lamps with a pleasant light' – no details) but the ceiling was also lowered in order to improve acoustics. Productivity in the quieter and 'more comfortably lit' work area increased by 8%, eventually dropping back to 6% a year later (thus not mere reaction to novelty). It is not possible to deem lighting alone responsible for this increase in performance;

- Boeing Assembly Plant: installed high efficiency metal-halide lamps were installed (employee control, an extraneous factor was also increased); workers' ability to detect imperfections increased by 20%;

- Hyde Tools, (manufacturer of blades) upgraded from old fluorescent lamps to high pressure sodium vapor[10] and metal-halide lamps, which made it possible to see specks of dirt which otherwise result in defective blades.

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[9] the authors inadvertently admit to this in their conclusion where they state: 'will just any retrofit produce gains in productivity? No, only those designs and actions that improve visual acuity *and* thermal comfort seem to result in these gains'.
[10] see Boyce and Simons (1977) and British Standards Institution (1967 & 68): high pressure sodium lamps producing worst scores in colour fidelity tests.

Estimates of improved quality are put at $25,000 a year, and it is calculated that every $1 saved on the shop floor is worth $10 in direct sales, hence the real improvement was $250,000;

- Pennsylvania Power and Light: upgraded with both high efficiency lamps *and* new ballasts, and also converted from general lighting to task lighting (which is normally under individual control and hence has a powerful influence on satisfaction) in the office complex housing its drafting engineers. The time required to produce a drawing dropped, thus boosting the productivity rate by 13%; and sick leave dropped by 25%, with a reduction in reported headaches at work (according to the superintendent);

- West Bend Mutual Insurance Company: *new* headquarters include an energy-efficient lighting system, better windows, more efficient HVAC system, individual temperature and ventilation controls, and environmentally responsive workstations. Productivity in the new building (in terms of number of files processed) increased by about 16%. Again, the role of light cannot be isolated;

- Lockheed Building 157: designed with 15-foot high windows, sloped ceilings and a central atrium, to bring *daylight* deep into the building. Daylight supplies most of the ambient light in the building. Unfortunately, from the point of view of isolating the daylight-productivity factor at least, interaction was also fostered by an open plan layout and large cafeteria; workstations were tailored to employee needs, and acoustic panels and chambers, sound-absorbing ceilings and even background ‘white noise’ installed to reduce ambient noise. Employee satisfaction ranged from spaciousness and décor, to workstation function and interactivity (due to sharing one building). Although productivity increased by 15% on the first major contract undertaken in the new building, the impact of novelty on morale is incalculable in the short term. Absenteeism also declined by 15 per cent. The effect of the daylight on these productivity gains cannot be extracted from this plethora of interacting variables.

- The Nederlandsche Middenstandsbank (NMB): *new* (in 1978) Amsterdam headquarters, a unique building with internal streets, plants, sculptures and ‘pulsing, gurgling’ fountains, and extensive *daylighting*. All desks are located within 23 feet of a window, interior louvres bounce daylight onto the ceilings, and atriums in the towers provide large amounts of interior lighting. Even coloured reflectors high in the atria bathe the space in coloured light. Absenteeism dropped by 15%, and this was attributed by managers to the ‘better environment’. Again, isolation of the daylighting effect is confounded by the many positive aspects of this novel building;

- The Wal-Mart: carries most weight with regard to the impact of *daylight* on productivity, despite the multitude of design features which also contribute to enhanced morale and improved work conditions. An atrium and special light-monitoring central skylights provide daylight to the building. Fortunately for our understanding of the daylight-productivity factor, the decision by the company to install only half of the skylights called for in the design – as a cost-cutting measure – inadvertently revealed an impact on productivity which has a high likelihood of being due to *daylighting* directly. Cash register activity reveals that sales per square foot are significantly higher for those departments located in the daylit half of the store compared to those without the skylights. Sales are also higher here than in the same departments in the companies other stores. *Here, due to this quirk, it seems possible to detect the influence of daylight alone.*

5 Conclusion

There is no doubt that light and human functioning are intimately related. This is a core and intrinsic environment-behaviour interaction of profound significance to life. If some doubts exist about the interaction of light *in buildings* and human performance it is due to the multitude of other dimensions which also bear on the issue; but nowhere is there evidence that better illumination (either in quantity or quality) has any negative effects.
With regard to lighting in the built environment, the emphasis is on 'performance' measures yet if there is one outcome of major import from this literature review it must be that a single 'prescription' must be acknowledged: the more natural the light the better adapted the organism. Hence, the more daylight and daylight-simulating artificial lighting which can be provided the better it is likely to be human performance, satisfaction, well-being and health.

Issues of increased capital costs (for glazing and/or full spectrum lamps) and potential energy savings due to the utilisation of solar-control glazing which is notably daylight-inhibiting or attenuating, and/or fluorescent lamps which are not full spectrum, pale into insignificance in comparison with the generic benefits which can accrue. In terms of productivity and hence competitiveness in the market and potential profit, it seems self-evident that upgrading lighting – in whatever manner – will deliver a more satisfied and healthier workforce, whether this is a derivative of the lighting alone…or in synergistic concert with many other powerful psychological dimensions associated with it.

Possibly the single most important technological advances required in this domain are: the combination of FSL and energy-efficiency - Vitalite® is already producing such a lamp[11]; and the manufacture of solar control glazing that minimises the attenuation of natural daylight.

…..Figure 1, overpage, symbolises a multi-dimensional integration…..

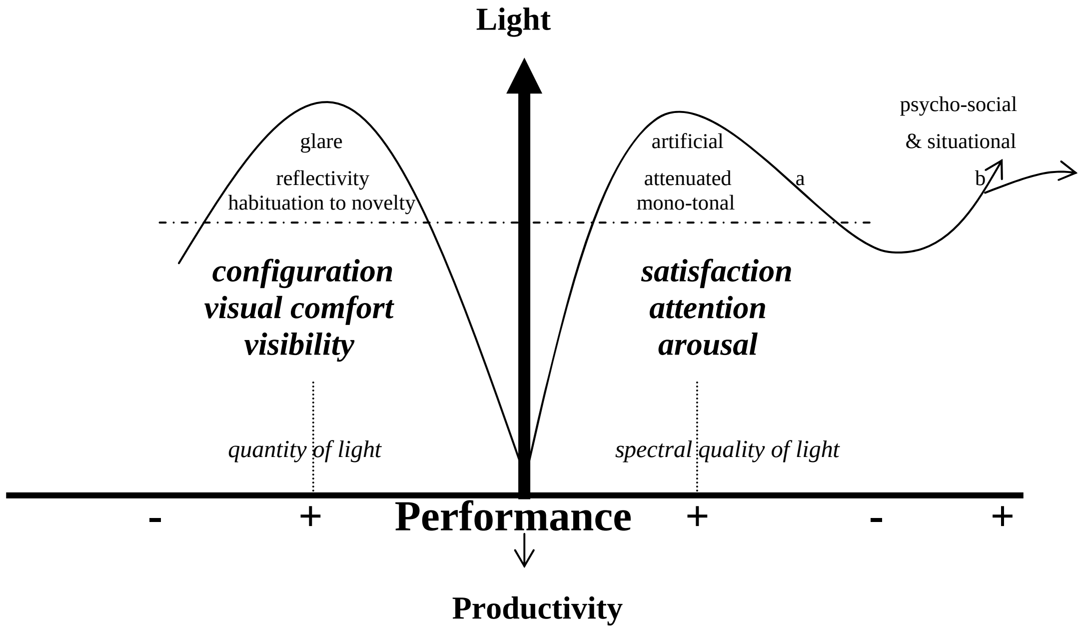

Figure 1: Conceptual Relationships between Light, Performance and Productivity: physical and psychological dimensions

[11] Ott BioLites are possibly the most advanced full spectrum lamps in terms of the biological light balance required for optimum performance (radiation shielded, UVA enhanced).

Quantity of Light:-

Visibility or visual acuity increases with increasing illumination, with a corresponding enhancement in task performance (particularly for smaller and/or more complex and contrasting visual tasks), and then progressively decreases at a certain level of illumination – where glare and veiling reflections *ie visual discomfort* (and, indirectly, even thermal discomfort) diminish performance and productivity. Generally, natural light is preferred and thus better tolerated than artificial light at equivalent intensities. Individual susceptibility will also vary according to experience, age, genetics. Furthermore, novelty increases performance until habituation occurs, with a corresponding decrease in productivity over time. *Configuration* refers to luminance distribution *ie* percentage of light on walls, ceilings and surfaces. There is a preference for situations where walls are also illuminated; which, fortuitously, is a natural characteristic of interior daylight.

Quality of Light:-

To the extent that light (in buildings) matches the natural spectrum of daylight, neuro-endocrine arousal and biological-clock regulation are enhanced, with an associated improvement in attentiveness, positive mood and satisfaction. As spectral quality diminishes (*ie* artificial lighting progressively diverges from natural daylight, and/or interior daylight 'attenuated' by transmission through glass) photo-chemical imbalance/stress increases - and symptoms such as lethargy and depression tend to occur. Furthermore, daylight not only naturally varies but also embodies salient information (time of day, weather conditions etc). This is experienced as more satisfactory than uniform/monotone light. At an indeterminate point (a) situational and psycho-social dimensions intervene *ie*: intentions, preferences, motivations, self-image, past experiences, status and responsibility (roles). These expectations and interactions are neither consistent nor are their consequences predictable (b); hence the difficulty of establishing any absolute relationship between light, performance and productivity.

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