Industrial lighting and productivity

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August 2002
Philips Lighting, The Netherlands

PHILIPS

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The three authors have an academic degree in physics respectively in electrical engineering (van den Beld). They joined Philips Lighting in the early respectively mid nineteen seventies. They have since been involved in fundamental lighting application research in many different application areas and in many different positions. They actively participate in the work of the International Commission on Illumination (CIE) and of the European standardization Technical Committee for Light and Lighting (CEN TC 169). They have individually presented papers at many different national and international Congresses and published in many renowned lighting journals. Wout van Bommel has been elected president of CIE for the period 2003-2007. Gerrit van den Beld is member of the Board of the Dutch Foundation "Lighting and Health" that promotes a wider medical-scientific knowledge of the influence of light on human beings. He is also member of the working group Light & Health, which is an initiative of the NSVV (Dutch lighting association). Martin van Ooijen is since 1992 the Convenor of the CEN Working Group "Lighting of Work Places.

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Summary

Good lighting on the task and in the workplace is essential for optimal task performance, especially with a progressively aging workforce. The effects of good lighting, extend much further since over the last two decades (medical) science has consistently shown the positive influence of light on health and well-being. Better lighting contributes positively to task performance (in terms of higher speed and lower failure rate), safety and accidents rate, absenteeism, health and well-being. In the metal industry, for example, good lighting can be expected to increase productivity by about 8 %.

Edition: August 2002

LIGHTING AND VISUAL PERFORMANCE

Industrial lighting covers a wide range of different working interiors and tasks: from small workshops to huge factory halls, and from fine precision work to heavy industrial tasks. The lighting quality should always be high enough to guarantee sufficient visual performance for the tasks concerned. A person's actual visual performance depends upon the quality of the lighting and of his or her own "seeing abilities". In this respect, age is an important criterion since lighting requirements increase with age. Figure 1 gives, as a function of age, the relative amount of lighting required for reading a well printed book. One of the many reasons for this effect, illustrated in Fig. 2, is the deterioration of transmittance of the eyes' lenses.

Fig. 1 Relation between age and light required for reading good print (Source: Fortuin [1]).

Fig. 2 Lens transmittance for various age categories. Values are expressed as a % of the 560 nm point for new born. (Adapted from Brainard et al [2]).

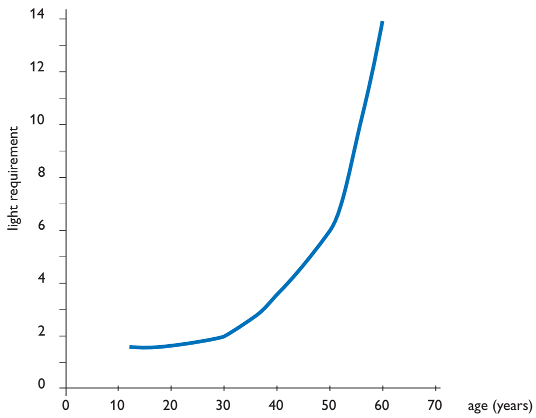

Fig. 1

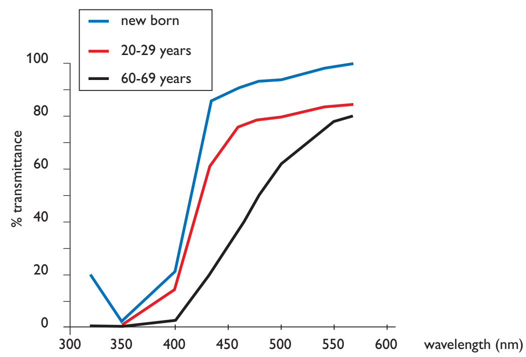

Fig. 2

Figure 3 gives an illustration of the many research results pertaining to the influence of lighting quality on visual performance. It gives the visual performance as a function of lighting level for different task difficulties. All tasks show a clear increase in visual performance with increased lighting level. The required lighting levels for the two tasks as specified in the European draft standard of CEN [3] are indicated. It shows that these CEN requirements are conservative if we take the effect of age into account.

Fig. 3 Relation between relative visual performance (in %) and lighting level (in lux) for a visually moderately difficult task (left) and for a visually difficult task (right). Continuous line: young persons. Broken line: older persons. (CIE [4]).

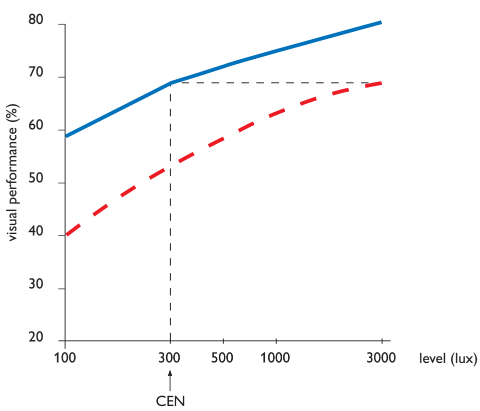

Fig. 3: visually moderately difficult task

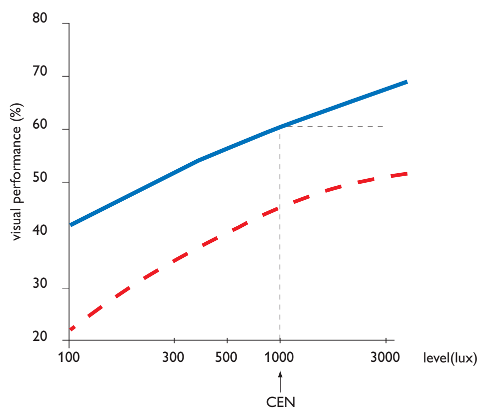

Fig. 3: visually difficult task

An improvement in visual performance, yields an improvement in task or work performance, reflected in a higher output and in a lower number of errors. The extent to which good quality lighting enhances work performance depends on the visual component of the task. A task with an important visual component will benefit more from good seeing conditions than a task with a less important visual component. Table 1 summarises for different industrial tasks the increase in task performance and the reduction in rejects brought about by an improvement of lighting quality.

Table 1 Increase in task performance and reduction in number of rejects as a result of improvements in lighting level. (Handbuch für Beleuchtung [5]).

Type of work	Lighting level (lux) Before	After	Increase in task performance (%)	Reduction in number of rejects (%)
Camera assembly	370	1000	7	-
Leather punching	350	1000	8	-
Composing room	100	1000	30	18
Fine assembly work	500	1500	28	-
Metal industry	300	2000	16	29
Difficult visual tasks in the metal industry	500	1600-2500	10	20
Miniature assembly	500-1000	4000	-	90
Weaving mill	250	1000	7	-

Table 1

LIGHTING AND THE WORKING ENVIRONMENT

If properly designed, the overall working environment can have a stimulating effect on the people working within it [6]. Today, a lot of emphasis is given to layout and interior design of the workplace, but lighting too plays an important role. Whilst it can emphasise positive elements of a design, lighting can also detract from these elements, for example by poor colour rendition or glare effects.

LIGHTING AND BIOLOGICAL EFFECTS

Light and the biological clock

Through a separate nerve system, ocular light sends signals to our biological clock which in turn regulates the circadian (daily) and circannual (seasonal) rhythms [7] of a large variety of bodily processes.

Fig. 4 Double plot (2 x 24 hrs) of typical circadian rhythms of body temperature, melatonin, cortisol and alertness in humans for a natural 24 hour light/dark.

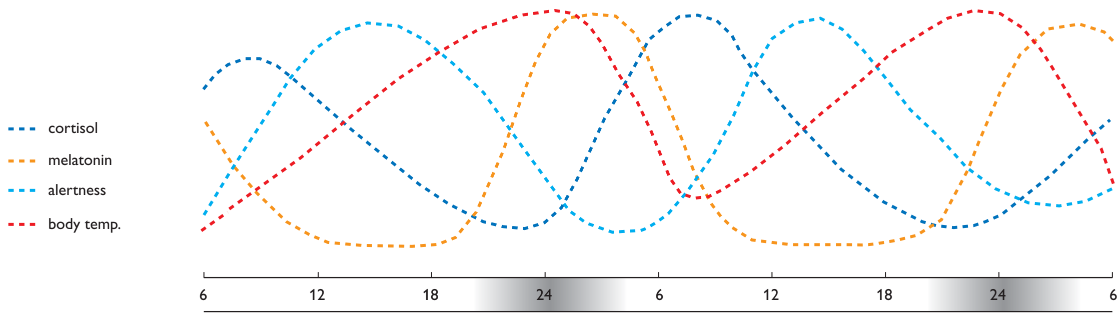

Fig. 4

Figure 4 illustrates some typical rhythms in human beings. The figure shows only a few examples: body temperature, alertness and the hormone rhythms of cortisol (stress hormone) and melatonin (sleep hormone). Important other rhythms are, for example, sleep-wake cycle, sleepiness, fatigue, mood and performance. The hormones cortisol and melatonin play an important role in governing alertness and sleep. Cortisol levels increase in the morning and prepare the body and mind for the coming day's activity. At the same time, melatonin level drops, reducing sleepiness. From these simplified examples, it is evident that both hormone rhythms are important for us to function well while we are awake and influence directly the degree of alertness.

Direct stimulating effects of light on the body

The direct stimulating effects of light are recognised by almost everybody, not only the differing effects of outdoor light in summer and winter, but also the effects of light in the interior environment [8]. This effect is partly psychological but there is also a physical component contributing to this. Differing light levels give changes in the EEG (ElectroEncephaloGraph) pattern, influencing the central nervous system and hence various body functions. Recent findings suggest, moreover, a direct effect of light on, for example, heart rate and insulin level [8], [9], [10].

Light, mood and alertness

In the industrial field, alertness is of prime importance as it is a factor in not only mood but also in performance and the avoidance of accidents. Many investigations on the effects of light on alertness and arousal level have been carried out under (night) shift-work conditions because the level in, for example, arousal would be lowest and consequently the effects to be expected would be strongest.

Fig. 5 Mood expressed as arousal level for uniform lighting levels of 250 lux (broken line) and 2800 lux (full drawn line) as a function of number of working hours for night-shift workers (Boyce et. al. [12]).

Fig. 6 Delta activity in the EEG of office workers under lighting levels of 450 lux and 1700 lux (Kuller, Wetterberg [16]).

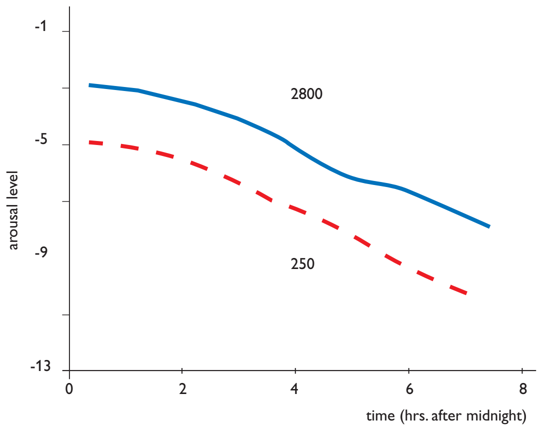

Fig. 5

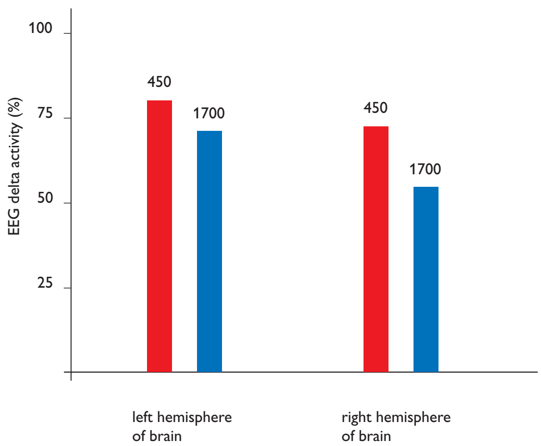

Fig. 6

Figure 5 shows the effect of two lighting regimes on arousal as a function of time at work for shift-workers [12]. A decline in arousal over the night occurs for both regimes, but the high-lighting regime results in significantly increased arousal level.

Other studies show that the use of higher lighting levels to cope with fatigue result in the subjects staying alert longer [13], [14], [15]. This is also reflected in the composition of EEGs containing fewer delta waves (which is an indicator of sleepiness), indicating that bright light has an alerting influence on the central nervous system (see Fig. 6).

Studies of stress levels and complaints in people working indoors have been made only in comparison with people working under a combination of electric light and daylight. These studies show that the stress in the group with the combined lighting was substantially lower in summer than in winter [17]. It can be assumed that the high amount of the daylight component in summer contributes to the reduced number of stress complaints. Bright light in winter can most probably compensate this difference [18].

Daylight and electric light

Indoor levels without daylight contributions are between 100 and 500 lux only and are usually determined by the requirement in the standard or recommendations. Fortunately, in many cases daylight contributions penetrate the buildings at least for several hours per day, increasing the overall lighting levels substantially. Another difference between daylight and electric light is the dynamics in level and colour temperature of daylight. It is generally accepted that these changes in daylight have a positive influence on mood and stimulation, and evidence exists to indicate that these positive influences can largely be duplicated with dynamic indoor lighting. An extensive study under office conditions has shown that people prefer high additional electric lighting in an office environment (average 800 lux on top of the prevailing daylight contribution) [19].

Effects of poor lighting quality

Working in poor or low quality lighting, people can suffer eye strain and fatigue, resulting in poorer performance. In a number of cases, it can lead to headaches [20]. Causes are in many cases down to a too low lighting level, glare from light sources and luminance ratios that are not well-balanced in the workplace and on the task. Headaches may sometimes be caused by lamp flicker, this being the result of using magnetic ballasts operating at the frequency of the electrical supply (50 Hz. In some cases, flicker can also cause stress in people [21]. Electronic ballasts operating at high frequencies of around 25 kHz do not exhibit flicker, resulting in reduced incidence of headache [20].

LIGHTING AND ACCIDENT REDUCTION

There is clear evidence that many types of industrial accidents can be avoided by providing better seeing conditions. Of course, the degree to which the number of accidents can be reduced depends to a great extent on the type of industry and the prevailing environmental situation. Table 2 gives the accident-reduction figures for two of the industrial tasks listed in Table 1, in which performance improvements and reject reductions were recorded.

Table 2 Accident reductions after improving lighting level. (Handbuch für Beleuchtung [5]).

Type of work	Lighting level (lux) Before	After	Accident reduction (%)
Metal industry	300	2000	52
Difficult visual tasks in the metal industry	500	1600-2500	50

Table 2

Figure 7, gives the number of accidents at the workplace as a function of lighting level for different types of injuries. Here, again, the trend is clearly a reduction in the number of accidents with improvements in lighting quality.

Fig. 7 Number of accidents for different industrial tasks as a function of the lighting level (347 accidents in-vestigated in total). (Völker, Rüschen-schmidt and Gall [22]).

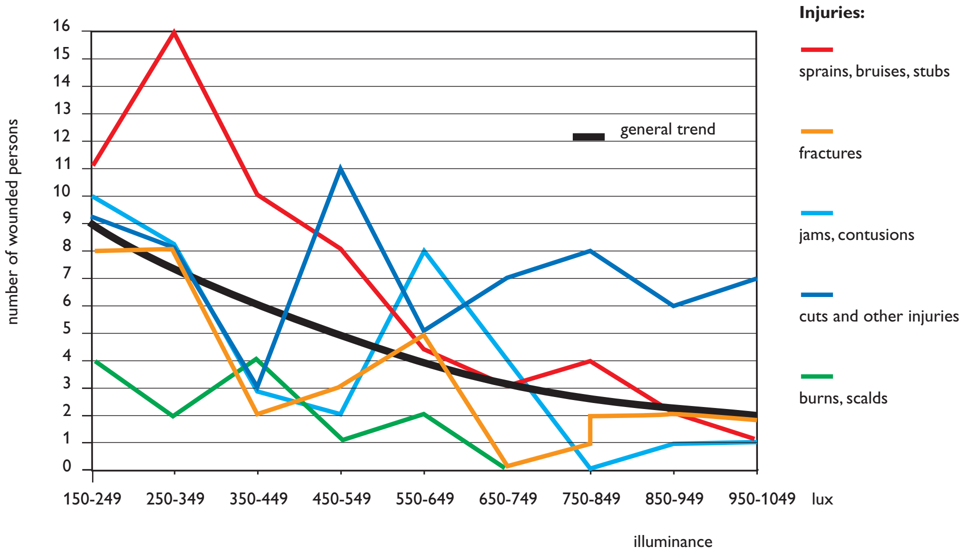

Fig. 7

It is important to note that not only the lighting level but all aspects of lighting quality play a role in preventing accidents. Here it suffices to mention that non-uniform lighting can create adaptation problems that hamper proper visibility. Excessive glare too leads to severe adaptation problems, with all the accompanying negative consequences. Moreover, stroboscopic effects of lighting can be hazardous in situations where it is important to correctly see moving parts of machinery, a danger which, it is worth noting, is completely eliminated by electronic high-frequency operated lighting. Finally, lighting giving poor colour rendering may lead to misjudgements of potentially dangerous situations.

LIGHTING AND PRODUCTIVITY

The metal industry has been chosen as the application for estimating the increase in productivity since earlier in this paper it was for this industry that data for increased task performance, reduction of rejects and the decreased number of accidents was provided.

Fig. 8 (Relative) consequences of increased lighting levels on task performance (a), number of rejects (b) and accidents (c) in the metal industry.

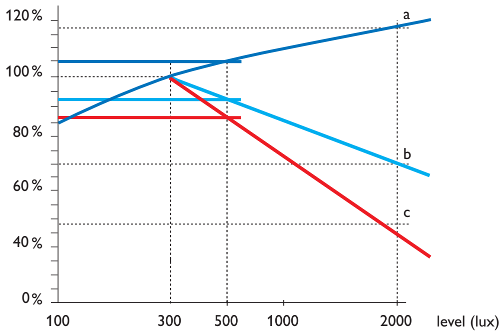

Fig. 8

Effects of increased lighting level

Reference here is made to Tables 1 and 2, which give quantitative data on the effect of increasing the illuminance in the metal industry from 300 lux to 2000 lux for:

- increase in task performance,
- reduction in number of rejects, and
- accident reduction

To be able to derive the data for an increase from 300 lux to 500 lux, it would be necessary to know the precise variation of the three effects between 300 lux and 2000 lux. Since this variation is not known (only the values at 300 lux and 2000 lux are known) some assumptions have to be made. It is very probable that the task performance follows the same course as the visual performance of Fig. 3. The course of this performance curve is therefore drawn between the 300 and 2000 lux points in Fig 8. in which the illuminance is represented on the horizontal axis and the task performance, number of rejects and number of accidents is represented on the vertical axis. As can be seen we assume for rejects and for accidents a linear relationship. From Fig. 8, the relative effects of a change in lighting level from 300 lux to 500 lux can now be determined. This is shown in Table 3 which also includes a bandwidth of uncertainty to allow for deviation from the assumptions. The table shows that increasing the lighting level in the metal industry from 300 to 500 lux produces an average productivity gain of some 8 % or between around 3% and 11% taking into account the bandwidth of uncertainty.

Table 3 Relative increase in productivity by increasing the lighting level from 300 to 500 lux in metal industry.

Metal Industry	Increased lighting level from 300 to 2000 lux (measured)	Increased lighting level from 300 to 500 lux (estimated)	Relative increase in productivity (300 to 500 lux)
Increase in task performance (%)	+ 16	+ 6 ± 3	+ 1,06 ± 0,03
Reduction in number of rejects (%)	- 29	- 8 ± 3	+ 1,005 ± 0,005 [1]
Accident reduction (%)	- 52	- 14 ± 5	+ 1,01 ± 0,01 [2]
Total relative increase in productivity			+1,075 ± 0,04

[1] in the metal industry, rejects will lead to some 2 to 5% loss of productivity
[2] accidents will lead in about 2 to 10% of the cases to actual absence of work and thus to loss of productivity. (In above table, 5% has been used in the calculations).

Table 3

Effects of increased overall quality of lighting

Lighting that fulfills the following criteria:

- sufficient light at the visual task,
- good uniformity of the lighting over the whole task area,
- balanced luminous distribution throughout the room,
- a lighting installation without glare,
- good colour rendering and appropriate light colour,
- lighting without flicker,

will increase workers' feelings of well-being and improve their motivation. Absenteeism will consequently be lower and productivity higher by an estimated additional 0.2 to 1.0% (not included in Table 3).

From the available data it is almost impossible to calculate the effect that better motivation with have on productivity.

CONCLUSIONS

The above analysis leads to the following conclusions for the metal industry:

- **Increasing the lighting level from the minimum required 300 lux to 500 lux leads to an increased productivity: based on realistic assumptions: more than 3-11%, on average 8 % but certainly to more than 3%.**

- **Using a good-quality lighting installation, a further increase in productivity of 0.2 to 1.0% is possible.**

- **The energy consumption (and thus the operating costs) of a good quality lighting installation at the increased level of 500 lux will in most cases be lower than that of the existing installation at 300 lux.**

- **Increasing the lighting level from 300 lux to 2000 lux increases productivity by 15 to 20%.**

- **For nightshift work at least the same productivity increases can be expected, i.e. 8% to more than 20%.**

REFERENCES

[1] Fortuin, G. J., "Visual power and visibility", Philips Research Report 6, (1951).

[2] Brainard, G.C. et al. "Action spectrum for melatonin regulation in humans: Evidence for a novel circadian photoreceptor", Journal of Neuroscience (2001).

[3] Draft European Standard prEN 12464, "Lighting of work places", (Comité Européen de Normalisation, CEN), (2001).

[4] CIE Publication 29.2: "Guide on interior lighting", (1986).

[5] Lange, H., "Handbuch für Beleuchtung", SLG, LiTG, LTG, NSVV, 5. Auflage, (1999).

[6] Clements-Croome, D., et al., "An assessment of the influence of the indoor environment on the productivity of occupants in offices", Design, constructions and operations of healthy buildings, ASHRAE, (1998).

[7] OTA, Congress of the US, Biological rhythms. US DOCS Y 3.T 22/2 2B 57/8.

[8] Mikellides, B., "Emotional and behavioural reaction to colour in the built environment", thesis Oxford, (1989).

[9] Ueyama, T. et al., "Supra-chiasmatic nucleus: a central autonomic clock", Nat. Neuroscience (1999).

[10] Scheer, F.A., et. al., "Light and diurnal cycle affect human heart rate: possible role for the circadian pacemaker", Journal of Biological Rhythms, (1999).

[11] Scheer, F.A., et. Al., "Light affects morning salivary cortisol in humans". Journal of Clinical Endocrinical Metabolism, (1999).

[12] Boyce, P.R., et. al., "Lighting the graveyard-shift: the influence of a daylight-simulating skylight on the task performance and mood of night shift workers", Lighting Research and Technology, (1997).

[13] Daurat, A., et. al., "Bright light affects alertness and performance rhythms during a 24-hour constant routine", Physics and behaviour, (1993).

[14] Grunberger, J., et. al., "The effect of biologically active light on the noo- and thymopsyche on psycho-physiological variables in healthy volunteers", Int. J. of Psychophysiology, (1993).

[15] Tops, M., et. Al., “The effect of the length of continuous presence on the preferred illuminances in offices”, Proceedings CIBSE Conference, (1998).

[16] Kuller, R. Wetterberg, L., "Melatonin, cortisol, EEG, ECG and subjective comfort in healthyhumans: impact of two fluorescent lamp types at two light intensities". Lighting Research and Technology, (1993).

[17] Kerkhof, G.A., Licht en prestatie. Proceedings. Symposium Licht en Gezondheid, Amsterdam, (1999).

[18] Partonen, T., et al., “Bright light improves vitality and alleviates distress in healthy people”, Journal of Affective disorders, (2000).

[19] Begemann, S.H.A., et. al., “Daylight, artificial light and people in an office environment, overview of visual and biological responses”, International Journal of Industrial Ergonomics, (1997).

[20] Wilkins, A.J., Nimmo-Smith, I., Slater, A., Bedocs, L., "Fluorescent lighting, headaches and eyestrain", Lighting Research and Technology, (1989).

[21] Kuller, R., Laike, T., "The impact of flicker from fluorescent lighting on well-being, performance and physiological arousal", Journal of Ergonomics, (1998).

[22] Völker, S., Rüschenschmidt, H., und Gall, D., “Beleuchtung und Unfallgeschehen am Arbeitsplatz”, Zeitschrift für die Berufsgenossenschaften, (1995).

[23] van den Beld, G.J. “Licht und Gesundheit”, licht 2002, Maastricht, (2002).

[24] van Bommel, W.J.M., et al., “Industrielle Beleuchtung und Produktivität”, licht 2002, Maastricht, (2002).

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08/2002 Printed in the Netherlands Data subject to change