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Rea, M. S.; Jaekel, R. R.

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by M.S. Rea and R.R. Jaekel

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RÉSUMÉ

On ne peut déterminer réellement à quel point l'énergie électrique est utilisée de façon efficace que si l'on évalue simultanément le fonctionnement du matériel électrique et l'occupation du local, puisque même de petites quantités d'énergie sont perdues si un appareil électrique est en marche sans être utilisé. Des nombreuses méthodes utilisées pour évaluer le taux d'occupation, celle où l'on effectuait des visites au hasard dans le local s'est avérée la plus précise et, en général, constituait le moyen le moins coûteux d'obtenir des données à la fois sur le fonctionnement et l'occupation. En utilisant davantage cette technique, les propriétaires et les exploitants de bâtiments pourraient évaluer si l'électricité est utilisée à bon escient dans les locaux qu'ils administrent.

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Summary To determine whether electrical energy is used effectively it is necessary to assess both operation of electrical equipment and occupancy of a space simultaneously, since even small amounts of energy are wasted if an electrical device is switched on but unused. Of the several methods of estimating occupancy that were compared, random visits to a space are the most accurate and usually the least expensive means of obtaining both occupancy and operation data. More widespread use of this technique would enable building owners and operators to evaluate the efficient use of electricity in the spaces they manage.

Monitoring occupancy and light operation

M S REA PhD and R R JAEKEL
National Research Council of Canada, Institute for Research in Construction, Ottawa, Ontario K1A 0R6, Canada

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1 Introduction

Efficient use of electricity is a reasonable goal in the design and operation of buildings. For accurate assessment of energy consumption, however, it is necessary to evaluate both the power supplied to the electrical systems and the total time the systems are operated. Present requirements to limit energy consumption in buildings are, perhaps surprisingly, seldom based upon more than limiting power density[1, 2] (i.e. watts per unit floor area). No doubt this is done for simplicity of regulation, and such methods probably do limit energy consumption by limiting the magnitude of half the energy equation. Requirements like these may not, however, lead to the most efficient solutions for reducing energy consumption. For example, use of a simple time switch may be more effective in reducing operational costs and electricity charges than limiting power density.

Such issues are well understood by the more sophisticated professionals, but even the clearest view of energy consumption does not provide a complete picture of efficient utilisation of electricity. Occupancy must also be taken into account in determining whether electricity is used effectively. The key word here is 'used'; if electrical energy is not used by an occupant, even relatively low levels of consumption are wasted. It is also conceivable that productivity may be reduced by occupants who are too frugal with the use of electrical equipment.

Occupancy is without doubt the least understood aspect of efficient utilisation of electricity. Certainly very few data are available on occupancy, partly because of the difficulty of obtaining reliable figures. What makes the situation even more difficult is that occupancy and energy must be evaluated simultaneously, since utilisation implies that occupancy and electrical consumption are coordinated. Although several techniques hold potential for monitoring occupancy and energy usage, no studies have compared them in terms of such issues as accuracy, cost and utility.

In the present study five techniques were employed to monitor occupancy in a frequently but intermittently occupied staff room. Although these five techniques represent the current practical methods for monitoring occupancy in buildings, only two of these techniques could also provide data on light operation. Both kinds of data are required to assess lighting operational efficiency properly, so the various techniques were compared in terms of utility for assessing both occupancy and wasted lighting energy.

2 Procedures

Five recording techniques were used to estimate occupancy in the selected staff room†: a personal visit, a video system, an infrared movement detector, an ultrasonic movement detector, and an electric eye. The Appendix provides relevant details.

The monitored staff room is a (6.0 × 8.8 m) community area with four windows (0.74 × 2.3 m) facing east and a south door to a hallway. Five toggle switches each controlling three two-lamp fluorescent luminaires are grouped on the wall next to the door. The room is used primarily as a coffee and lunch room, but on occasion staff members have meetings or work there for short periods. With these exceptions, occupancy is intermittent and brief.

For a three-week period from 11 February to 1 March 1985 simultaneous recordings for the five techniques were obtained between 0800 and 1700 h on each of five working days (Monday to Friday). Although data were collected with each recording technique, it was not necessary to use all the values for the analysis. Correctly implemented sampling procedures can yield statistically identical information with much less effort[3]. For this experiment one minute of each monitored hour was randomly and independently sampled, giving 135 samples of occupancy (9 h on each of 15 days) for each recording technique. Data were recorded for each sample as 1 for occupied or 0 for unoccupied. Similar recordings were made for light operation (1 for on, 0 for off) with both the visit and the video techniques.

Depending upon the recording technique, slightly different methods were used to acquire the sampled data for analysis. With the visit technique, one of the experimenters walked quickly past the staff room at the appointed minute and recorded on a checklist the number of people in the room and whether any of the five light circuits were on.

† Room 350, Building M–24, National Research Council of Canada, Ottawa, Canada

With the video system, a frame on the tape corresponding to the appointed minute was visually inspected after all monitoring was completed‡; as with the visit technique both occupancy and light operation were recorded. With the infrared and ultrasonic techniques, points were located on the event recorder strip-chart corresponding to the sampled minutes; occupancy was assumed if the strip-chart record showed a deflection at that point. Finally, with the electric eye technique the very narrow spikes on the strip-chart indicating breaks in the beam were usually too narrow to hit during a sampled minute. After completion of the study these very narrow deflection periods were increased by widening each spike symmetrically along the time axis, and thus increasing the chances for a hit during a sampled minute. Several deflection periods were arbitrarily chosen corresponding to response intervals of 1.0, 5.0, 12.0, 20.0, 30.0 and 60.0 min. As for the infrared and ultrasonic techniques, a point was located on the (modified) strip-chart record corresponding to the randomly sampled minute; occupancy was assumed if the sampled point was within the widened deflection period. Light operation could not be gleaned, of course, with these last three techniques.

3 Results

3.1 Observed occupancy proportions

The proportions of time during which the staff room was occupied according to the five recording techniques and their associated methods of acquiring the data are given in Table 1. These 'occupancy proportions' are based on the sum of zeros or ones obtained from each random and independent sampling method divided by the total number of samples (N = 135).

3.2 Inherent bias

Clearly, the various techniques provide different estimates of occupancy proportions in the staff room, even though the data were collected simultaneously. The differences are largely due to biased estimates of occupancy (both positive and negative) associated with the various methods and not to the variability created by random and independent sampling procedures. The magnitudes of the different types of bias associated with the five recording techniques are illustrated and described mathematically in Figure 1; all the biases could be estimated prior to data analysis.

The visit and video techniques were unbiased. With a completely random and independent sampling procedure there should be no opportunity for systematic bias. The only deviation of estimated from actual occupancy should be due to small, random variability due to the sampling procedure. (In this case the difference in occupancy proportions obtained from the two techniques was about 6%.) Thus, in Figure 1 the relation between actual occupancy and estimated occupancy is expected to have a slope of one and pass through the origin for both techniques.

‡ The data acquisition methods used with the video system were analogous to those employed by Rea and Jaekel[3] using time lapse photography with a Super 8 movie camera. The video system was used instead of the movie camera, because video systems are now more readily available and easier to use. Further, the video tapes can be inspected immediately after data acquisition which are less susceptible to loss or destruction due to inadequate care when processing.

Table 1 Occupancy proportions for the five recording techniques

Recording technique		Occupancy proportion†
Visit		0.50
Video		0.53
Infrared		0.79
Ultrasonic		0.56
Electric eye:	1 min	0.28
	5 min	0.62
	12 min	0.79
	20 min	0.90
	30 min	0.93
	60 min	1.00

† All occupancy proportion values were determined from completely independent random samples except those associated with the electric eye; these were all obtained using the same random sample.

The bias associated with the infrared technique is relatively simple to determine. As it responded to the last movement detected in the room, its bias was positive and nominally constant at 12 min. (Laboratory tests showed that the delay period varied between 11.77 and 11.97 min, the latter representing the typical value.) That is, it continued to signal movement for a fixed 12 min after the last motion was detected. Assuming a constant average positive bias of 12 min, the relation between actual occupancy and estimated occupancy should have a slope of one and an intercept of 12 min (Figure 1).

The bias associated with the ultrasonic technique depended on the typical occupancy period. The detector responded to the first movement in the space and, although

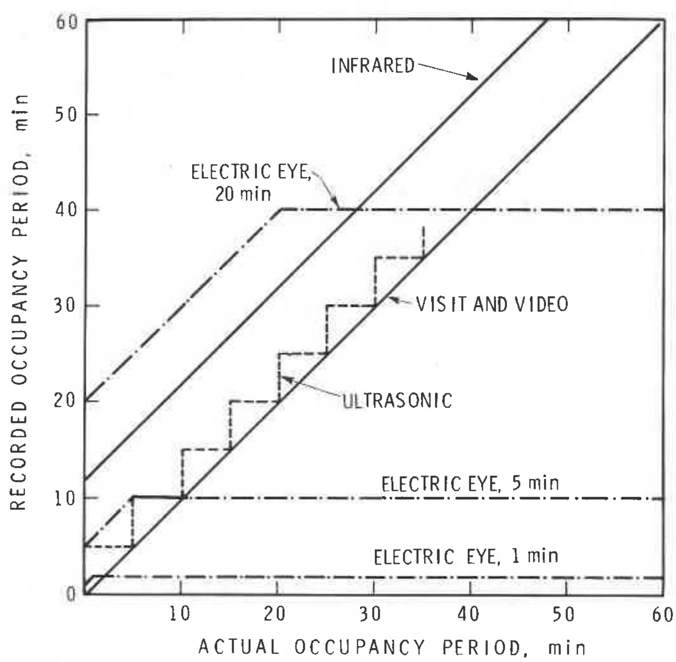

Figure 1 Inherent biases associated with different recording techniques. Bias is the difference (in min) between actual and recorded occupancy periods. Visit and video techniques, bias = 0; infrared technique, bias = 12 min; ultrasonic technique, bias = r where r is the time in min remaining in the occupancy period to complete the 5 min response cycle; electric eye technique, bias = x min if occupancy period $\leq x$ or $2x$ min minus occupancy period if occupancy period $> x$ where x is response interval (e.g. 1, 5 or 20 min)

unresponsive to more movement, continued to signal movement for a nominally fixed period of 5 min. (Laboratory tests showed that the delay period varied between 4.30 and 4.42 min, values in the middle of the range being typical.) Thus, the ultrasonic technique would be positively biased by as much as 5 min if the typical occupancy period was very brief. The positive bias becomes progressively smaller as the typical occupancy period increases up to 5 min, when the bias approaches zero. For longer occupancy periods this pattern of positive bias cycles every 5 min (Figure 1).

The bias with the electric-eye technique depends upon the chosen width of the modified response intervals (spikes) in the record. As for bias with the ultrasonic technique, the electric eye bias depends upon the typical occupancy period. The modified, widened spikes associated with entry and exit from the space overestimate occupancy proportions for very short occupancy periods. (Widened spikes indicate occupancy before entry and after exit.) For very long occupancy periods, however, occupancy proportions can be underestimated. (Spikes may not be widened enough to indicate occupancy between entry and exit.) As illustrated in Figure 1, the degree of positive or negative bias depends on the width of the modified spikes and the typical occupancy period.

To obtain an accurate estimate of biases for the ultrasonic and electric eye techniques it was necessary to estimate typical occupancy periods from the video tapes of the staff room during the monitoring session. Thirty combinations of hours and minutes within a working day, two for each day monitored, were sampled randomly. The duration of occupancy for a given sample was taken to be the length of stay by a single occupant immediately after or during the designated day, hour and minute. If there was more than one occupant at the designated time, occupancy duration was taken to be the length of stay for the last occupant to enter the room before the designated time. Further, two unusually long visits to the room by one of the experimenters were ignored. Based upon the 30 samples obtained by these rules the median length of occupancy was 2.43 min. This median value, taken to represent the typical occupancy duration, can be used to estimate the degree of bias in techniques which depend on time of occupancy.

Figure 2 shows the estimated biases plotted for the observed occupancy proportions for the five recording techniques. Although there is an apparent functional relation between the observed occupancy proportion and the bias inherent in the recording technique, the relation is not general enough to be used in other situations§. Since a functional relation between occupancy proportion and bias always depends upon both occupancy frequency (i.e. how often occupants enter the room) and occupancy duration (i.e. how long occupants stay in the room), a bias-free recording technique must be employed to assess occupancy

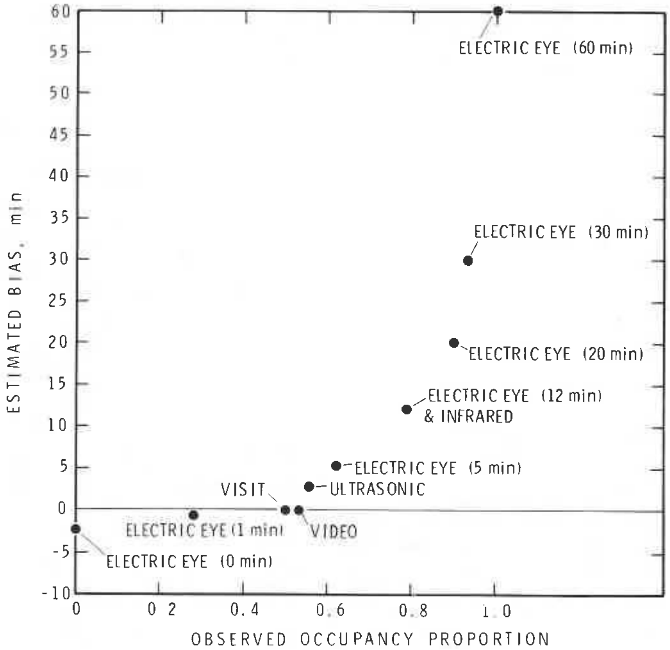

Figure 2 Estimated biases and observed occupancy proportions for the different recording techniques and methods of data acquisition, assuming a 2.4 min typical occupancy period

proportion accurately. The visit and video techniques were the only two which were not biased and therefore the only two which provided accurate estimates of occupancy proportion.¶

3.3 Light operation

As noted in the Introduction, it is important to relate lighting energy operation to occupancy. Table 2 shows two sets of estimates, one each from the video and visit techniques, of the proportion of time the lights were operated in the staff room and how that relates to occupancy. Estimates of light operation by the two techniques are close, and the differences between them are similar to the differences obtained for occupancy. These are similar in magnitude to those observed by Rea and Jaekel[3] when directly comparing sampled data with all available data.

It is interesting that occupancy proportions exceeded light operation proportions in this study. It was clear from the visits and the video tapes that the occupants relied heavily on daylight in the room, and that light operation was considerably less when the curtains were open than when

Table 2 Light operation proportions and associated occupancy proportions for visit and video techniques

Mode	Visit	Video
Light operation (L)	0.42	0.39
Occupancy (O)	0.50	0.53
Coordinated light operation and occupancy (LO)	0.27	0.24
Lights on but no occupancy (w)	0.16	0.14
Occupancy but no light operation (NO)	0.24	0.28

Although $L = LO + w$ and $O = LO + NO$, rounding to two significant figures produces slight discrepancies in the tabulated sums.

§ A general and consistent relation between occupancy proportion and bias would permit a derivation of the actual occupancy proportion, once the inherent bias had been determined.

¶ The ultrasonic and infrared techniques could probably be modified to eliminate any bias and therefore provide accurate estimates of occupancy proportion. Perhaps too, the electric eye could be modified to provide unbiased data (e.g. coupled with an 'intelligent' data acquisition system distinguishing between entry and exit). Nevertheless, none of these can provide simultaneous lighting operation data. They cannot, therefore, provide by themselves the data necessary for evaluating the efficient use of electrical energy.

Table 3 Cost of obtaining light operation data and occupancy proportions (15 days)

Cost category	Visit	Video	Ultrasonic	Infrared	Electric eye
Equipment and materials	\$3 for paper and clipboard	\$250 for camera and video recorder rental; \$240 for tapes	\$600 for detector & event recorder; \$35 for chart paper	\$700 for detector and event recorder; \$35 for chart paper	\$600 for detector and event recorder; \$35 for chart paper
Set-up and checking time	0 h	1 h at \$20 h^{-1}, camera and recorder	1 h at \$20 h^{-1}, detector and recorder	1 h at \$20 h^{-1}, detector and recorder	1 h at \$20 h^{-1}, detector and recorder
Random numbers for sampling	1 h at \$20 h^{-1}	1 h at \$20 h^{-1}	1 h at \$20 h^{-1}	1 h at \$20 h^{-1}	1 h at \$20 h^{-1}
Data reading	12 h at \$5 h^{-1}, personal visits	16 h at \$5 h^{-1}, viewing tapes	8 h at \$5 h^{-1}, reading chart paper	8 h at \$5 h^{-1}, reading chart paper	8 h at \$5 h^{-1}, reading chart paper
Data entry	1 h at \$5 h^{-1}	1 h at \$5 h^{-1}	1 h at \$5 h^{-1}	1 h at \$5 h^{-1}	1 h at \$5 h^{-1}
Total	\$88†	\$615	\$720	\$820	\$720

† This cost estimate represents the most efficient use of time during the personal visits, approximately 5 min per visit. Costs could be as high as \$703.00 if only one room was visited each hour. See also Appendix.

they were closed; this was true although occupancy proportions did not vary substantially. More will be said about these findings in another study.

3.4 Wasted lighting energy

Rea and Jaekel[3] presented a simple formula for determining wasted lighting energy based on the difference between the proportion of occasions lights were on in a space and the proportion of occasions the space was occupied (i.e. $w = L - O$ in Table 2). No provision was made in this formula for uncoordinated light operation and occupancy. With the original formula, wasted lighting energy could not be evaluated accurately if, for example, subjects worked in daylight alone. This did not happen in the tests originally reported by Rea and Jaekel, but daylighting is an important issue in the present study. Consequently, the formula originally derived by Rea and Jaekel should be modified to reflect wasted lighting energy more accurately. By the new formulation

$$w = L - LO \qquad (1)$$

where w is the proportion of lighting energy wasted, lights on but no-one in the space, L is the proportion of time lights are on in the space, and LO is the proportion of time lights are on and the space is occupied.

Using Equation (1), the proportion of wasted lighting energy was approximately 0.15 (Table 2). (Although some lighting energy was wasted, there seems to have been an attempt by occupants to reduce lighting energy consumption in this area.)

3.5 Cost of data acquisition

Cost is an important consideration in the evaluation of occupancy recording techniques. Table 3 provides estimated data acquisition costs for the different techniques. It was assumed that only one recording technique had been used and that the least expensive option would be employed. Computerised data acquisition systems, for example, were prohibitively expensive and therefore ignored. Technician and student assistance were valued at \$20 h^{-1} and \$5 h^{-1} respectively. The less expensive student assistance was utilised whenever possible. More details may be gained from the Appendix.

It should be noted that all techniques other than the visit would be much more expensive if more spaces within the building had been monitored; the cost of the visit technique would remain essentially the same. Conversely, cost of the visit technique depends on the number of monitored days.

4 Discussion

To assess the efficient utilisation of electricity accurately it is necessary to collect data on operation and occupancy simultaneously. To this end only one technique studied in this report, namely, the personal visit technique, seems both practical and useful for evaluating lighting energy consumption. Although as accurate as the personal visit, the video technique seems impractical. It is probably quite vulnerable to theft or vandalism in some areas which might be of interest. It may also be intidimating and induce occupants to behave differently, although there is no concrete evidence for this in the present study. Monitoring a number of areas by the video technique would increase costs proportionally, but, as mentioned previously, little additional cost would be incurred by the personal visit technique. The single distinct advantage of the video technique is that it can provide a permanent record for multiple review.

The biases associated with the ultrasonic, infrared and electric eye techniques seriously compromise their utility for monitoring occupancy. Although there may be obvious methods of eliminating such biases, there are at least four other reasons for favouring the personal visit. First, set-up of each system probably requires more than basic technical skills for installation and maintenance. Second, only occupancy data can be obtained, and to evaluate efficient utilisation of electricity properly, data on operation need to be collected simultaneously. Third, the personal visit (or the video) offers much richer data than are possible with the other techniques. It may be of interest, for example, to collect data on other aspects of the space such as use of other electrical devices, window blind usage, or multiple occupancy. Fourth, by using the personal visit more data can be collected from other spaces in a building with little additional cost. Instrumenting several rooms and then evaluating the acquired data would be prohibitively expensive. As argued against the video technique, theft and vandalism may also increase costs. Without doubt, the personal visit is the outstanding method for obtaining occupancy and operation data.

Acknowledgements

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Appendix: Description of recording techniques

Personal visit

The equipment required to obtain data consisted of a clipboard and a sheet of paper. One table listing all the appointed times for the visits adjacent to spaces for light operation and occupancy could be conveniently arranged on the single piece of paper. Total cost would not exceed $3.

The appointed times for data acquisition were obtained from a published table of random numbers. (Most elementary texts on statistics include such a table.) The data table took about an hour to prepare. Personal visits to the space required less than 5 min per visit, and this value was used in the cost estimate. Without proper utilisation of employee time, however, the cost for data acquisition would increase to as much as $703.00, representing one visit per room per hour. Data entry into a computer file took about 1 h.

Video system

Video equipment consisted mainly of a colour video camera (JVC GX-N5V, $900), super wide-angle lens ($100), and recorder (Panasonic PV-6110K, $1300). Miscellaneous cables and mounting fixtures were required, as was a quartz watch, which was hung in front of the wide-angle camera lens. Video tapes also had to be purchased ($240), making total costs of about $2550; equipment rental would be about $250 for the experiment, and this value was used in Table 3.

Installation of the video camera and recorder and checking their operation took about an hour. As with the personal visit, a data table with random sampling times and spaces for light operation and occupancy had to be prepared. The data table facilitated video tape data acquisition from the television monitor. Examination and maintenance (changing and storing) of the tapes required about 16 h, with an additional hour for data entry.

Infrared

The infrared system was a fluorescent/incandescent lighting control (Tishman and United Technologies detector, Model 628-1, with controller, Model 629-1, $200). The detector sensed rapid changes in the ambient level of infrared radiation created by occupant movement in the space. When activated, the detector closed a relay contact that nominally lasted for 12 min (actual values were between 11.77 and 11.97 min). Although the contact remained closed, the detector was sensitive throughout this period and could continue to sense movement. Output from the infrared system was recorded by an analogue event recorder (Watanabe Servocorder, Model SR652-SHE). (Less expensive strip-chart event recorders can easily be obtained for about $500.)

It took about an hour to mount and align the detector properly as well as to check system operation. As with the visit and video techniques, preparation of a data table for strip chart data acquisition took about an hour. Data acquisition and data entry into a computer file took about 9 h.

Ultrasonic

The ultrasonic system was an intrusion alarm (Safe House, Model 49–303, $100) employing the Doppler effect whereby motion-induced changes in the emitted ultrasonic frequencies are detected. A change in the echo frequency, caused by movement in the room, produces a 12 V DC signal that nominally lasts 5 min (actual values were between 4.30 and 4.42 min). The system cannot sense additional movements during this period. Output from the ultrasonic system was recorded on the same analogue event recorder as was used for the infrared detector. System installation, data acquisition and data entry costs were similar to those for the infrared system.

Electric eye

The electric eye was also an intrusion alarm (Safe House, Model 49–307, $100). A focused infrared source and detector were mounted on one side of the staff room door and a reflector was mounted on the opposite side. The focused beam was aimed at the reflector, which was then aimed at the detector adjacent to the light source. An interruption in the reflected beam indicated entry or exit from the room. Beam interruption is recorded on the analogue event recorder used for the infrared and ultrasonic detectors. System installation, data acquisition and data entry costs were similar to those for the infrared and ultrasonic systems.