

Three-process model of supervisory activity over 24 hours

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Objectives This study used endogenous and exogenous factors to develop a model for sampling supervisory activity that implied consulting numerous data on computer systems. .

Methods The study was carried out in an automated workshop of a chemical plant. Five crews worked on a 3×8 hour shift system, with changes at 0400, 1200 and 2000. Each team included 2 experienced controllers who supervised the process from computer systems in a control room. Starting and ending duty at the same time as the operators, the researchers used real time to code of all the screen pages selected on the computers by 8 controllers (from 4 teams) over 18 shifts.

Results The time-of-day fluctuations of the call frequency confirmed the existence of endogenous factors (biological rhythms or fatigue), but they cannot explain all the variations observed. The modeling of the data yielded the following 3 explanatory factors: (i) the cognitive demands of the tasks, as an external factor, mainly concern the impact of shift changeover characterized by a strong peak of information gathering at the beginning of the shift, even at 0400; (ii) the shift duration appears as a “fatigue” factor and reflects a rapid reduction of information gathering over the shift; (iii) circadian rhythms are characterized by a minimum of activity at night and a maximum in the afternoon.

Conclusion In other similar work situations, in addition to an essential work analysis, our model could help the design of shift duration or schedules for shift changeover.

Key terms complex system, control room, information gathering, shiftwork arrangements, supervision modeling.

Working in dynamic complex systems such as refineries and chemical and nuclear plants requires operators to cope with 2 types of work constraints, namely working on a rotating schedule (generally on 3×8 hour or 2×12 hour shift systems) and performing a supervisory activity with high mental demands.

The rotating shift systems involve working and reasoning during day and night shifts. But many studies have shown that circadian rhythms influence the operators' performance (1, 2). The differences appear in cognitive tasks such as visual research, memorization, logical reasoning and information processing (3, 4). Investigations in actual work situations (particularly in automated complex processes) offer similar results. During regular operation (without incident), the controllers do not operate and supervise a complex system in the same way at different times of the day (5). The variations appear in the

frequency and the type of information gathering in a control room (6). Clearly, these variations may have serious consequences for the safe running of complex systems. For example, in nuclear plants, the number of human errors increases over the night shift, but also at the beginning and the end of the morning and afternoon shifts (7).

The cognitive demands of tasks have increased through the evolution of new supervisory computer systems (greater complexity and size of installations) that have modified the presentation of information. Therefore, due to the partition of information, a controller needs to consult several screen pages to check the proper operation of the process. This selective information gathering (the operator cannot see all the information he needs at any one time) will depend on the operator's mental image of the function of the system (8). The operator will generally form this image at the start of the shift by

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memorizing previous process data. In this way, the incoming operator can check what happened in the workshop during his absence. During the remainder of the shift, he or she briefly samples information to update his or her image of the process (9, 10). This sampling activity is essential for the supervision of a complex system which consists of the prevention of and recovery from malfunction. In both cases, the mental image enables the past and present states of the system to be identified and the future status of the system to be predicted in order to guide action (11, 12, 13).

To study the effects of the workhours and the cognitive demands of the tasks involved in the operation of supervisory computer systems, we have applied available models (2, 14, 15, 16, 17) that emphasize the masking effect of external factors on circadian rhythms. With this approach we have attempted to develop a model of process operating behavior; the model takes cognitive demands, type of shift, and time into shift into consideration.

Subjects and methods

The study was carried out in an automated workshop of a chemical plant. The continuous process produced ammonia from natural gas. Five teams of 8 male operators worked in shifts to supervise the operation of the process on a rotating schedule (2 mornings, 2 afternoons, 2 nights and then 4 rest days) with shift changes at 0400, 1200 and 2000. Each team was supervised by a foreman. It included 2 controllers who supervised the system from the computerized control room, while 4 patrollers and 1 assistant shift foreman worked outside in the plant itself. The 2 controllers shared the process supervision. Each of them was officially responsible for only some parts of the system. This work distribution did not differ during or between the shifts.

The control room was equipped with 5 computer consoles displaying data on about 2400 parameters over 600 screen pages. Each screen page displayed a specific identification code comprising 1 letter and 3 digits at the top left.

We investigated the supervisory activity of 8 controllers between 35 and 50 years of age. Each of them had long experience with shift work (more than 10 years) and also with the job (5 years to more than 10 years). After 1 month of familiarization, they were observed during their regular work without any monetary incentive to participate.

Data were collected through observation and scoring (in real time) of all the screen pages selected by the controllers. This recording required 2 researchers to control fluctuations in vigilance and to allow for successive breaks. They stood behind the computer screens in order

to be able to see and take notes on each display. Later, the recordings of both researchers were compared and then transcribed to computer files. The scorers started and ended their duty period at the same time as the operators did. In this research, we did not study the whole shift change-over; instead we focused on the work period after the departure of the outgoing operators. Therefore, the observations only concerned the incoming controllers' activity.

Data were collected over 18 shifts, equally divided between the 3 shift periods (6 morning, 6 afternoon and 6 night shifts) to analyze the effect of workhours. From these data, we studied the frequency of consultation, the type of information displayed, and the consultation sequences over the different shifts (18). In this report, we have taken only the mean number of screen pages accessed per hour into account. A repeated-measures analysis of variance using Greenhouse-Geisser correction was performed. Then we developed the model of sampling activity applying a nonlinear regression with Systat software (19).

As performance and behavior could vary according to the state of the process, particularly if there was an emergency, we only analyzed the controllers' activity during normal operation of the plant (excluding also maintenance periods). Under these conditions, the controllers' task generally did not differ between the shifts.

We also controlled a few additional factors. The number of operators behind the monitors was recorded, bearing in mind that the display access was essentially reserved for the 2 controllers. Therefore each of them always used 2 computers, and the fifth remained available for the other members of the team. No significant effect was found for the number of operators working at the monitors.

During the study, the controllers could choose the time and duration of their "informal" rest period. We recorded this information, but there was no time effect of the rest period on the activity because there was neither regularity in their occurrence (the operator could leave the control room either at the beginning, the middle or the end of the shift) nor in their duration.

Results

Description of sampling activity over 24 hours

We initially verified the distribution of the hourly rate of screen pages (black curves) selected over the 3 shifts (figure 1). Each shift was divided into eight 1-hour blocks from the beginning to the end of the shift. It can be seen from figure 1 that there was a considerable variation in the rate of consultation on the screen pages within a shift [$F(7,77) = 11.82$, $P < 0.001$; after the Greenhouse-Geisser

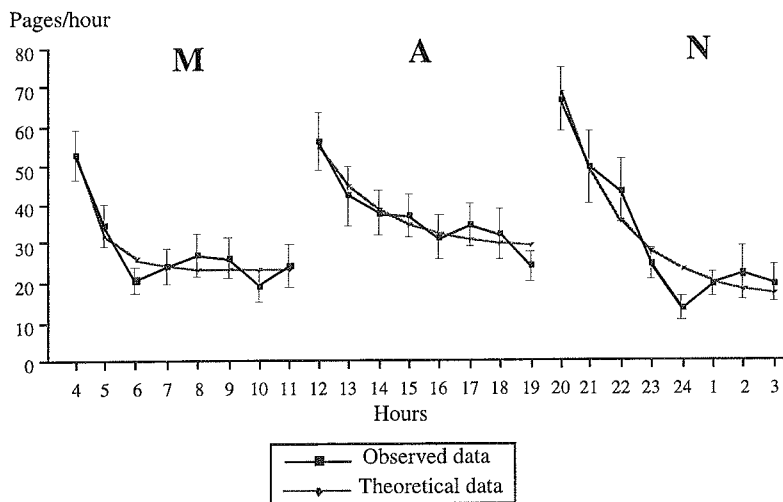


Figure 1. Mean hourly frequency of pages (observed data in black line) displayed during the shifts and the standard error of the mean. (M=morning, A=afternoon, N=night)

correction], characterized by a consultation peak at the beginning of the shifts, followed by a decrease. But, due to the importance of shift changeover, there was no significant effect of type of shift [$F(2,22) = 2.68$, $P > 0.09$]. Nevertheless, this evolution into the shift depended on the type of shift. In other words, there was an interaction between the shifts and the duration of work [$F(14,154) = 1.99$, $P < 0.02$].

Let us consider the 2 results. First, during each shift, the operators' activity was characterized by a high frequency of consultation at the beginning of each shift (0400, 1200 or 2000) during almost the first 2 hours of work. During the remainder of the shift, the rate of consultation decreased and led to a basic level of supervision.

We estimated the asymptotic level of the curve to determine when this basic rate was reached. It appeared when the frequency of consultation remained stable around a mean value. We called this work phase "the body of the shift", where the controller really supervised the process. Confirming previous data of controllers' activity, the latter was found to depend on the time of day, the maximum occurring in the afternoon (an average of 30 screen pages selected per hour) and the minimum at night (18 screen pages per hour). It was reached more or less quickly depending on the shift: within 90 minutes in the afternoon, after 120 minutes in the morning, and after about 3 hours at night.

Therefore the controllers' activity varied within a shift and consisted of 2 main stages (figure 2), namely, the shift changeover and the supervision period (basic level of supervisory activity).

The mean frequencies at the start of the shift differed significantly from those later in the body of the shift. The controllers' activity was 2 or 3 times higher during the shift changeover [$F(1,11) = 32.1$, $P < 0.001$] than during the supervision period, but the difference between the 3

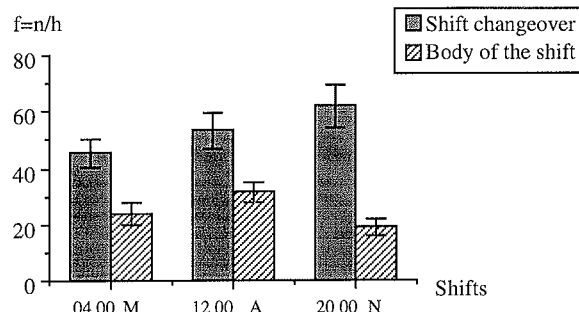


Figure 2. Mean hourly rate of consultation of screen pages (f) during shift changeover and during the body of the shift (normal supervision) (ie, last 5 hours of shift) and the standard error of the mean. (M=morning, A=afternoon, N=night)

shift changeovers was not significant [$F(2,22) = 2.41$, $P > 0.1$]. On the other hand, an analysis solely based on the body of the work (the last 5 hours of supervision) revealed a significant variation between the 3 shifts [$F(2,22) = 4.15$, $P < 0.03$]. These hourly differences were confirmed by the significant interaction between the shifts and the 2 stages (beginning and body of the shift) [$F(2,22) = 6.78$, $P < 0.01$]. This time-of-day effect can be more clearly distinguished in figure 3.

As does figure 1, figure 3 represents the hourly call frequency over 24 hours. When we joined the equivalent points of the curve, a "circadian-like" component appeared. For example, with the 1st hour of work, the 2nd hour of work, and the 6th hour of work.

Three-process model of the supervisory activity

For each shift, we developed a model of the supervisory activity (figure 4), as based on the hourly frequency of consultation over 24 hours (figure 1). First, the data were carefully described to eliminate noise and enable the appropriate framework to be drawn so that a mechanistic interpretation of the process would be possible.

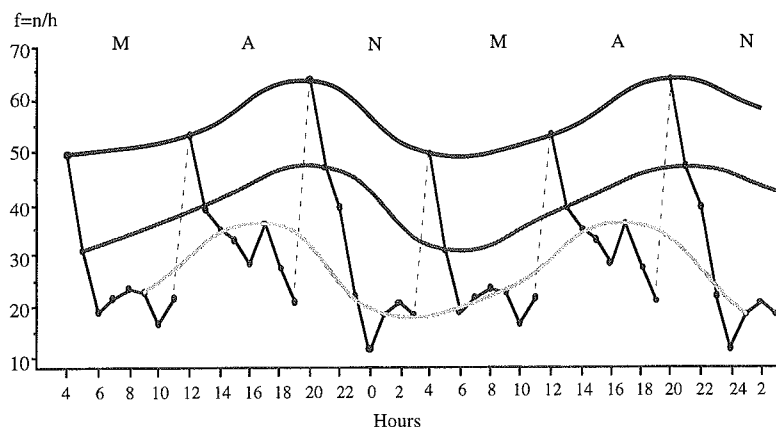


Figure 3. Mean hourly frequency of consultation over 2x24 hours and a representation of the circadian component (in grey curves). (M=morning, A=afternoon, N=night)

Model

$$A(t) = P_1 + (P_2 - P_1) \cdot \exp(-P_3 \cdot t)$$

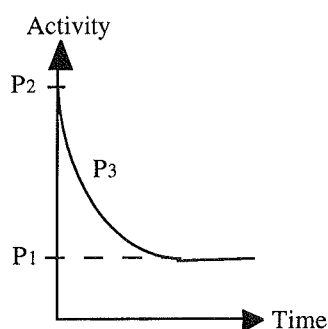


Figure 4. Three-process model of information gathering. [A(t)=activity(t), P₁=basic level, P₂=maximum, P₃=decreasing factor, t=time]

Table 1. Estimated values of the different components of supervisory activity according to the model. (M=morning, A=afternoon, N=night).

Description	Parameters	Shifts		
		M	A	N
Basic level	P ₁	23.204	28.335	14.293
Maximum of consultation	P ₂	52.943	54.577	68.265
Decreasing factor	P ₃	1.239	0.476	0.464

The first descriptive step led us to build a model with the following 3 components: (i) a basic level reached asymptotically (P₁), (ii) a maximum activity at the beginning of the shift (P₂), and (iii) a decreasing factor (P₃).

To model the decrease of activity, we tried a first-order decreasing factor. As the fit was good (grey curves in figure 1), according to the principle of parsimony, we did not try to fit a second-order decreasing rate. By a first-order decreasing factor, we refer to the instantaneous

decrease of activity being proportional to the instantaneous activity, the coefficient of proportionality being P₃. Thus we assumed that A(t) denotes the activity at time t, Δt represents the change in time, and A(t+Δt) is the activity at time t+Δt. Then a first-order decreasing rate was defined by (A(t+Δt)-A(t))/Δt=-P₃ A(t).

After algebraic manipulation, we obtained the model represented in figure 4.

It is clear that the created model cannot fit the data exactly; therefore the model which had to be used had to have another term (denoted εt), which measured the differences between the data and the model presented previously. Thus the following statistical model was arrived at: A(t) = P₁ + (P₂ - P₁) exp(-P₃·t) + εt.

Applying nonlinear regression (19) to the empirical data, we obtained the parameters shown in table 1.

The variations in the information gathering over the 3 shifts were correctly explained by the model (observed and theoretical data in figure 1). The goodness of fit was assessed by the calculation of R² (90.9%, 89.3% and 92.1% for the morning, the afternoon and the night shifts, respectively).

Discussion

Three interactive factors of supervisory activity

Presumably, the beginning of the morning shift (0400) is characterized by a low level of vigilance and a short previous sleep (20). Therefore, the existence of a relatively low peak of consultation and a large decreasing factor (P₃=1.23) revealed a major effort to update the operators' mental image. As assessed by the operators, early morning hours quickly result in weak vigilance and low fatigue level. Thus they try to verify the state of the process more rapidly, when compared with the other 2 shift changeovers. In the afternoon, a high and increasing level of vigilance favors the persistence of a high level of activity over the shift (weak slope of the curve).

Finally, at night, the highest level of consultation peak occurs (68 pages per hour) due to a maximum of vigilance at the end of the afternoon (at 2000). It then decreases to a minimum of 14 pages per hour, a value coinciding with the decrease in alertness in the middle of the night.

The results show that the supervisory activity found in the present study depends on 3 main factors (figure 5). First, there is a workhour effect (or time-of-day effect, represented by the letter "C"), which leads to variations as predicted by chronobiological models. It is represented by a sinusoid with the lowest level in the middle of the night, an increase in the morning until a maximum in the evening. But, as already discussed, the data do not permit a firm conclusion about circadian effects. The second factor is a shift duration ("D"), which induces "fatigue", followed by a decrease in sampling activity (oblique lines in figure 5). No ratings of fatigue were really reported, but interviews with the operators and the record of postural, motoral, and verbal activities (21) suggested this effect. Moreover, from previous studies carried out in the same work situation and with the same operators, various measures (urinary cortisol) confirmed classical and well-established results concerning circadian variations (22). The third factor was task demands ("P"), particularly during the shift changeover. These demands are represented by a peak of consultations as compared with the basic level (horizontal line).

The interaction between the 3 factors (represented by $C \times D \times P$) leads to the 3 different evolutions, depending on the shift, observed in the supervisory activity (lower part of figure 5). According to our data, these evolutions are represented by 3 different curves.

Towards applications of the model

The classical sinusoidal model found in chronobiology cannot explain all the variations in observed operators' activity, such as a strong peak of consultation at 0400. The supervisory activity involves an interaction between the effect of biological rhythmicities and other external and internal factors. The cognitive demands of the task, which mainly concern the differences between the 2 work stages, and particularly their impact at the time of shift changeover, can mask, in part, the effect of circadian rhythms.

Our model was developed for a particular work situation and during regular operation. Thus generalization must take into account these conditions. Even if it concerns specific work situations (automated process control), we can however emphasize that, in any other situation, the impact of some task demands can modulate the time-of-day effect (14, 15). Whatever the process state (regular or not), the operators have to start their duty and update their mental image of the system at the start of the shift. Thus, even if an incident occurs, the shift changeover effect always appears more or less strongly. During a specific shift, an incident emergency will certainly

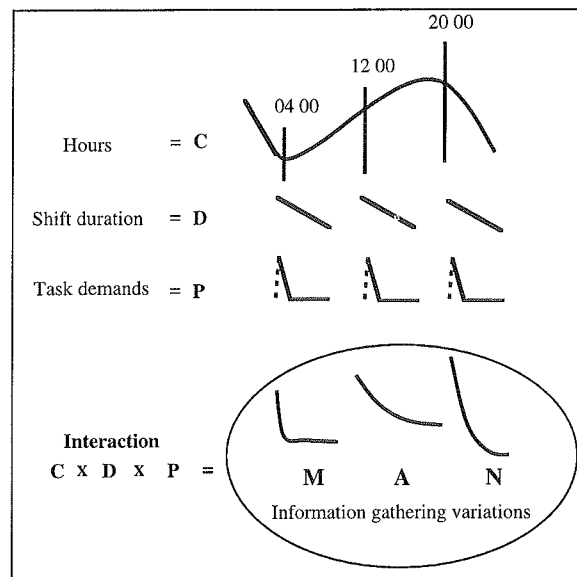


Figure 5. Three factors determining supervisory activity and information-gathering variations resulting from interaction of the factors according to the shift. (M=morning, A=afternoon, N=night)

influence the supervisory behavior at that moment (increase in the number of screen pages selected), but this kind of situation is punctual and independent of the time of day and does not disturb the model generalization over several days. On the average, the model predicts general and predominating behavior. Nevertheless, one may assume that the speed of the decreasing rate depends on the work load. This assumption needs, of course, further empirical validation. Nevertheless, some results presented recently showed a comparable evolution of activity over a 12-hour shift, in a power station (23).

If the model describes supervisory activity correctly, it may also lead to predictive hypotheses. Thus some applications of the model in the determination of work schedules could be inferred, in addition to an essential analysis of actual work activity to define job constraints.

For example, a computerized simulation based on the model could help the design of the best-shift duration. In a work situation, if the decreasing factor (P3) appears to be very high, it could be concluded that a short time is necessary to update the mental image or that the work constraints cause severe fatigue. Then it would be desirable to implement short shifts. On the other hand, a lower decreasing factor could reflect a long time to update the image or a lower level of fatigue induced by the work constraints. In this case a 12-hour shift would be acceptable. Furthermore, if the updating period is costly for the operator (that is, if he has to make a major effort to consult and memorize a large quantity of information at the beginning of the shift), it would be better to reduce the number of shift changeovers during the circadian cycle and

thus profit by the updating for a longer time.

For work content and the consultation peak (P2), we could examine the schedule from a shift changeover point of view. As cognitive demands are always present at the beginning of the shift (the operators must update their mental image of the process whatever the shift), we can assume that these demands require effort that varies according to the time of day. In this case, the circadian constraints are important. We have noticed that the consultation peak is higher at 2000, when the level of vigilance is highest, than at 0400, when it is lowest. This finding suggests that 0400 is a bad hour for shift changeover and may lead to an unreliable mental image.

Another implication of the analysis is the importance of a staggered shift changeover. Our results showed a strong consultation peak during the 1st hour of work. If the entire team starts the shift at the same hour (as in the situation studied), all the operators have to update their image of the system at the same time, and none of them are totally operational during the 1st hour of work. The shift changeover is therefore a critical period for security. On the other hand, if the operators do not start their shift at the same time (some of them could successively arrive in the workshop every 30 minutes), there will be at least 1 operator who is operational. Moreover, much more information would be checked during 2 hours, and the probability of detecting a problem would increase. The shift changeover is then less critical.

From these 3 examples, we emphasize the necessity to supplement our model by analyzing actual work activity. The combination of these 2 methods could help to determine work schedules according to work load and reliability.

Conclusions

Supervisory activity varies according to the shift, and it results from the interaction between the effects of work hours, duration of shift, and cognitive demands of the tasks. This interaction is represented by a high level of mobilization during the shift changeover, followed by a progressive decrease to reach a basic rate of consultation. This latter corresponds to the supervision period. From an applied point of view, such a model would be helpful when shift duration and the time and duration of shift changeovers are being planned.

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