Chapter 3

Analysis and Design of Cognitive Task Load

This chapter presents the development of a cognitive task analysis which assesses the task load of jobs and provides indicators for the redesign of jobs. General principles of human task performance were selected and, subsequently, integrated into current task modeling techniques. The resulting cognitive task load analysis centers around four aspects of task load: the number of actions in a period, the ratio between knowledge- and rule-based actions, lengthy uninterrupted actions, and momentary overloading. The method consists of three stages: (i) construction of a hierarchical task model, (ii) a time-line analysis and task load assessment, and (iii), if necessary, adjustment of the task model. An application of the cognitive task load analysis in railway traffic control showed its benefits over the “old” task load analysis of the Netherlands Railways. It provided a provisional standard for traffic control jobs, conveyed two load risks —momentary overloading and under-loading— and resulted in proposals to satisfy the standard and to diminish the two load risks.


Keywords: Cognitive task analysis, mental load, railways, traffic control.

3.1 Introduction

The first research question of this study is: how to allocate tasks to computer users so that each user can execute his or her part of the job well? A general analytical method to assess the correspondence between the task demands and the task performers’ knowledge and capacities, a cognitive task analysis, could contribute to such a task allocation and, consequently, lead to improved human involvement in man-machine systems (Rasmussen, 1986; Woods & Hollnagel, 1987; Roth & Woods, 1989; Roth et al., 1992). This chapter centers on the harmonization of task demands to the cognitive capacities of task performers. The following chapters center on the design of an aiding facility to harmonize the task demands to computer users’ knowledge.

Several methods for task analysis have been developed to assess the demands of work (see for example Fleishman & Quaintance, 1984; see also chapter 2). A classical approach towards workload assessment was to subtract the time required for the execution of the actions from
TABLE 3.1: Components in Shafer’s (1987) model: \[ \text{workload} = f(\text{things to do}) \times (\text{level of complexity}). \]

<table>
<thead>
<tr>
<th>Things to do</th>
<th>Level of complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>Tracking precision of movement</td>
</tr>
<tr>
<td>Mentals</td>
<td>Things in memory precision of recognition</td>
</tr>
<tr>
<td></td>
<td>Mental tasks precision of calculation</td>
</tr>
<tr>
<td></td>
<td>Information load level of ambiguity</td>
</tr>
<tr>
<td>Visual</td>
<td>Things to see ambiguity of presentation</td>
</tr>
<tr>
<td></td>
<td>Visual input</td>
</tr>
<tr>
<td>Vocal</td>
<td>Spoken commands precision of speaking</td>
</tr>
<tr>
<td></td>
<td>Communication signal-noise ratio</td>
</tr>
<tr>
<td>Hearing</td>
<td>Communication signals</td>
</tr>
</tbody>
</table>

TABLE 3.2: The Criterion Task Set consists of nine types of tasks. For each task type, referring to specific processing stages, three load levels are distinguished.

<table>
<thead>
<tr>
<th>Processing stages</th>
<th>Task type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input/perceptual</td>
<td>Probability monitoring</td>
</tr>
<tr>
<td>Central Processing</td>
<td>Continuous recall/recognition</td>
</tr>
<tr>
<td></td>
<td>Memory search</td>
</tr>
<tr>
<td></td>
<td>Linguistic processing</td>
</tr>
<tr>
<td></td>
<td>Grammatical reasoning</td>
</tr>
<tr>
<td></td>
<td>Mathematical processing</td>
</tr>
<tr>
<td></td>
<td>Spatial processing</td>
</tr>
<tr>
<td>Motor/output</td>
<td>Interval production</td>
</tr>
<tr>
<td>Input/output</td>
<td>Unstable tracking</td>
</tr>
</tbody>
</table>

the available time. This approach did not take the diverse complexity of mental work into account. Therefore, new approaches have been developed in which workload is a function of the number of task components in a period and the complexity of these components; examples being analyses based on the Criterion Task Set (Amell et al. 1987) and Shafer’s (1987) analysis of task components (see also Drury, 1983; Drury et al., 1987). Table 3.1 provides an overview of the task components in Shafer’s model in which workload is a function of the “things-to-do” and the “level-of-complexity”. The components are a kind of check-list to compare the workload of different tasks. The second example provides a somewhat different classification of human actions, that is, the Criterion Task Set consists of nine types of tasks; each burdening specific processing stages (see table 3.2). For each task type, the standard task set provides three tasks with different load levels (low, medium, and high). The question is still how to relate the task set, and the corresponding research results, to complex real-world tasks. In general, analyses of specific task components or isolated laboratory tasks address only certain aspects of human information processing and have not considered, for instance, the effects of experience on mental workload (Wierwille, 1988). The methods are useful for evaluations of specific task demands, but are insufficiently suited for a compound analysis of task load in complex cognitive work.
Next to these workload analyses, task modeling techniques have been developed which comprise the complete task. A well-known technique in ergonomics, time-line analysis, provides an overview of the process of task execution (e.g., Laughery & Laughery, 1987; Parks & Boucek, 1989; Gray et al., 1993). However, current time-line analyses are hardly sensitive to covert actions, such as planning and rehearsal (Wickens, 1992). A second well-known technique, hierarchical task modeling, can be used to derive a complete overview of the task and allocations of subtasks to human or computer (e.g., Sebilotte, 1988; Diaper, 1989; de Greef & Breuker, 1992; Neerincx & de Greef, 1993; Shepherd, 1993). Such modeling can convey cognitive processes involved in the execution of simple tasks (Card et al., 1983), but it is still rather unclear how to model human capacities involved in the execution of complex, data-driven tasks with large uncertainties such as design (see chapter 2).

In sum, the methods and techniques presented above address the cognitive demands of work insufficiently or they center around a detailed analysis of a limited set of cognitive tasks. A major problem is that a complete, unifying set of principles which generally apply to human performance is not available (Fleishman & Quaintance, 1984; see also chapter 1). However, some general principles of human information processing are noted in cognitive theories. The analysis of cognitive demands of a complete, and possibly complex task, may be achieved by integrating these principles into current task modeling techniques. Although the scope of such a method will be limited to a restricted set of principles, it may help to improve the current practice of task load management.

In a preliminary study, principles were selected and an attempt was made to describe a number of Computer Aided Design (CAD) tasks in terms of these principles (Neerincx, 1990, 1992). Particularly the application of Rasmussen’s (1983) information processing model appeared to be useful for the assessment of cognitive task load, because it takes task complexity and task experience into consideration. Based on this model, a time-line analysis was developed which provided an overview of the task execution, called action chart, conveying the dynamics of task load. In cooperation with the Netherlands Railways a project was initiated to extend this analysis and develop a method for the assessment of the task load of jobs, which could provide indicators for the redesign of jobs to overcome load problems. The investigative approach is pragmatic: try to integrate knowledge about cognitive processes into a comprehensive analysis technique consisting of hierarchical and time-line modeling. The research consists of five steps: (1) distinguish general principles of cognitive processes, (2) based on these principles formulate general guidelines for an optimal cognitive task load, (3) combine hierarchical task modeling and time-line analysis in one method and integrate the guidelines into the method (the result is the cognitive task load analysis), (4) apply the method, and (5) compare it with a classic method. Section 3.2 describes the cognitive principles and guidelines. Section 3.3 describes the cognitive task load analysis. Section 3.4 reports upon an application of this method in railway traffic control and section 3.5 compares it briefly with the “old” load assessment method of the Netherlands Railways. The last two sections of this chapter consist of, respectively, the conclusions and discussion of this investigation.

### 3.2 Cognitive Task Load

When assessing physical loading one can observe whether the forces exerted on the person’s body match the anatomical and physiological capabilities of the person performing the task. An
assessment of cognitive capacities should, in a similar manner, compare the task demands with the cognitive capacities of the task performer (cf., Gopher & Donchin, 1986). The task load is optimal if the task demands agree with the capacities; the loading must not be too high or too low (Parks & Boucek, 1989; Wiener et al., 1984; Gaillard, 1993).

Whilst the assessment of physical loading is based on knowledge about the anatomy and physiology of the human body, the assessment of cognitive task load will have to be based on knowledge of cognitive processes. This section discusses briefly a number of process characteristics which are important to an analysis of task load. The study centers around general limits of cognitive processes in which working memory and attention are involved (Baddeley, 1992), as distinguished from perceptual and motor processes. Theories with a narrow focus are excluded and individual differences are not considered. First, the limits are briefly discussed and, subsequently, four guidelines are presented for the harmonization of the task to the limited capacities of human information processing.

Cognitive Processes

Level of Information Processing. Rasmussen (1983, 1984) distinguishes three levels of information processing: skill, rule and knowledge (see also Reason, 1990). Although this framework was developed for the analysis of errors in process control tasks, it also appears to be suitable for a more general analysis of task load. The three levels define a qualitative division of loading: the higher the level of information processing, the higher the task load. Chapter 2 discussed the three level of information processing; here, a brief summary with it’s implication for cognitive task load is presented.

The skill-based level represents routine actions that, after a statement of an intention, take place as smooth, automated and highly integrated patterns of behavior. The performance is characterized by feed-forward control. The rule-based level represents problem solving actions in which the solutions are governed by stored rules (productions) of the type “if <state> then <action>”. The performance is also characterized by feed-forward control. The knowledge-based level comes into play in novel situations for which actions must be planned. Based on a mental model, the person sets local goals, initiates actions to achieve them, observes the extent to which the actions are successful and, if needed, poses new subgoals to minimize the discrepancy between the present position and the desired state. Control is primarily of the feed-back kind.

An important characteristic is that the level of information processing drops as task experience grows (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). The complexity of the task, next to experience, determines the level of information processing. Task complexity is defined by the ease of rule- or routine-“compilation” (cf., Kieras & Polson, 1985; see chapter 2). Simple tasks can be performed according to a few number of rules, whereas complex tasks encompass of uncertainties which compel the task performer to plan a unique procedure for each specific situation so that rule-based shortcuts cannot be developed (see Rasmussen’s step ladder model in Figure 2.1). The relationship between the above-mentioned hierarchical framework and task load can be summarized as follows: the more complex the task and the lesser the experience, the higher the level of information processing and the higher the task load is.

Interference. In general, various cognitive processes are involved in the execution of a task. The task load is not a simple summation of the load of the individual processes. Interference between concurrent information processes increases task load. The interference is minimal when the processes refer to different dimensions such as the spatial and the linguistic dimension.
Therefore, driving a car (the spatial dimension) and talking to the passenger (the linguistic dimension) may occur concurrently. Summarizing, the interference principle states that the interference between cognitive processes is less if they draw on different dimensions and that these processes are therefore less burdensome than processes which draw on the same dimension.

*Capacity Fluctuations.* Human capacities are affected by changes in the state of the person. During continuous work, the task performer may become fatigued or bored and, consequently, the task performance may be impaired. Fatigue is the result of prolonged continuous work, while boredom is the result of repetitive and monotonous task executions. Rouse (1988) maintains that if the human has just completed a difficult task, the capacity to carry out another task can be reduced (the carry-over effect).

**TABLE 3.3:** Task performance at time of day as a function of task type. Task type is defined by the cognitive processes and the memory entailing the main performance limits.

<table>
<thead>
<tr>
<th>Task type</th>
<th>Performance at time of day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task requires immediate information processing, task load is low (long term memory)</td>
<td>Performance increases from morning to afternoon</td>
</tr>
<tr>
<td>Immediate memory task (short term memory)</td>
<td>Performance decreases from morning to afternoon</td>
</tr>
<tr>
<td>Complex task, task load is high (working memory)</td>
<td>Performance is best during midday</td>
</tr>
</tbody>
</table>

Further, human beings possess a biological clock, that is, their biological functioning and corresponding capacities follow circadian rhythms like an oscillator with a cycle’s length of about 24 hour. In general, performance is better in the daytime than at night. The effects of time of day on task performance are summarized in table 3.3 (Hockey, 1986; Craig *et al.*, 1987; de Vries-Griever & Meijman, 1987). Capacity fluctuations make it necessary to examine the course of cognitive processes in time: the negative effects of under- and overloading may increase in the course of the task execution.

**Guidelines for Harmonization**

Several important characteristics of cognitive processes were described above. To what extent can we absorb the knowledge of these processes in the cognitive task analysis? It must be usable by the task analyst in a relatively simple manner, like guidelines.

Rasmussen’s distinction between skill-, rule- and knowledge-based actions seems suitable to address demands on cognitive capacities for task load analysis. Ultimately the cognitive task analysis must also take into consideration any possible interference between cognitive processes. There is no general interference model which encompasses all possible dual task performances and provides simple rules enabling one to predict multiple task performances (see chapter 2). Consequently, the task analysis presented here will not consider interference between actions performed simultaneously.

In general, the cognitive principles discussed above show the importance of variation in the
task. Variation in the level of information processing prevents under- and overloading. Variation in the cognitive dimensions which are involved in the performance of the task reduces the likelihood that the capacity of the task performer will be diminished as a result of boredom or fatigue. Assessment of task load should encompass of variation in task complexity and variation in the process of task execution in addition to the time available for task execution. Four general guidelines comprise these important load aspects: the first two center on an overall assessment of the time available and the variation in complexity, while the last two center on an assessment of the variation in the execution process (see Figure 3.1). Following these guidelines should result in a fine harmonization of the task to the above-described capacities of the task performer. The next section provides an overview of the cognitive task load analysis, which assesses a task on the basis of these four guidelines.

I. The total number of actions in a period should have an upper and a lower limit so that there is sufficient time to carry out these actions.

II. The task must call for several levels of information processing. Skill-based actions are barely cognitively demanding; the ideal ratio between rule- and knowledge-based actions in cognitive tasks has an upper and a lower limit.

III. There should be no long-term period in which only one sort of skill-based action is performed continuously. In a vigilance task, a performance decrement can appear, for instance, as early as after 10 minutes of continuous work (Tiffin & McCormick, 1965; Levine et al., 1973; Parasuraman, 1986).

IV. There should be no momentary overloading: several knowledge-based actions do not have to be performed in rapid succession within a short period of time or it is not necessary to perform almost simultaneously rule- or knowledge-based actions. In these two situations good task performance is actually not possible and it will be accompanied by errors or sub-optimal solutions.

FIGURE 3.1: Guidelines for the harmonization of the task to human capacities.

3.3 Cognitive Task Load Analysis

The cognitive task load (CTL) analysis is directed at the harmonization of the task demands to the capacities of the task performers, so that they do not become under- or overloaded. In the method the guidelines are integrated into a combination of hierarchical task modeling and time-line analysis. The first objective is the analysis of existing situations to convey under- and overload and the derivation of propositions for the redesign of task load. In future research it must be investigated whether the method can also be applied in the design of man-machine systems to assess and compare different task envisionments.

The CTL-analysis comprises three stages. The first stage consists of modeling the task to get an ordered description of the task allocations, the jobs and the actions. The second stage is a specific kind of time-line analysis, in which scenario’s —actual task performances or design
proposals— are tested against the four guidelines of Figure 3.1. If problems are notified, the third stage is entered in which the task model is redesigned to improve the task load.

**Stage I: Hierarchical Task Modeling**

The aim of the hierarchical task modeling is to arrive at a neat arrangement of all tasks that are allocated to man. A tree provides a nice overview of the task and may prevent the analyst from becoming lost in details. Furthermore, in the third stage of the task analysis, measures for task load improvements can be formulated as changes in the tree. The modeling technique, task decomposition, is an iterative process. Decomposition can stop when subtasks are allocated to the machine, that is, when they are completely automated (cf., de Greef & Breuker, 1992; for an assessment of such task allocation, see Brouwers & Neerincx, 1989). The task analyst creates the tree on the basis of observations, existing documents and interviews. The resulting tree is presented to one or more experts for verification and may be altered as a result of this.

**Task Allocation.** In the first instance, the task breakdown stops if all task allocations to persons can be designated within it. According to our definition of a job as a set of tasks allocated to one person, jobs are established this way. The railway traffic control task, for example, can be decomposed in three subtasks: (1) deal with irregularities, (2) carry out the work plan and (3) provide information to the passengers (see Figure 3.2). The three subtasks comprise all task allocations: one person may be responsible for one, two, or all three subtasks (cf. roles, Curtis et al., 1992).

**Task Breakdown per Job.** For the study of the individual person working on a task, the task needs to be decomposed in more detail (cf., Shepherd, 1993). The resulting tree is a static structure which recursively enumerates the different types of subtasks involved in a task. It may be tempting to read the tree as a sequential control structure saying that each of the subtasks must be executed in turn. This is not intended; the aim of the CTL-analysis is not to produce an executable model of the task. The tree provides a neat arrangement of all possible subtasks. Not all subtasks have to be actualized in a specific task instance.

Interviews with how and why questions —referring to lower respectively higher levels in the hierarchy— and expert-verification result in a tree that is quite natural (Sebilotte, 1988). It may be helpful to describe the objects used in the task and link them to the tree (Diaper, 1989). Leaf tasks are the subtasks at the lowest level of the tree; they will always be performed on an object, like a telephone, planning form or keyboard, and will cause a change of state in this object. In practice, with most leaf tasks there is actual change of physical objects. Shepherd’s (1993) leaf tasks comprise, for example, control changes to the system, such as operating pumps and valves. Sometimes there will be no physical object involved in a leaf task, but instead a “cognitive object”, such as memory will be involved in planning. A traffic controller may, for example, alter the short-term planning of train routes in his or her memory without communicating it to other
personnel.

So far, the task is modeled as a tree with a static structure. The hierarchical task model describes what the traffic controller does, that is, the cognitive tasks bringing about changes in objects. The model also encompasses why the subtasks are performed, because a (sub)task is defined in terms of the task performers’ goals. The task hierarchy can be viewed as a high-level GOMS-model without the methods and selection rules (see chapter 2). The model will be extended with a description of how the task is performed (i.e., a description of the so-called methods and rules).

Behavioral View. A behavioral view on the tree establishes the dependencies between the leaf tasks, so that they can be described in terms of skill-, rule- and knowledge-based actions. Most leaf tasks are observable actions, but some are purely mental (i.e., without motor activity). The mental, covert tasks are —together with an observable task— part of a single problem solving activity according to Rasmussen’s step ladder model (see Figure 2.1). The combination of a purely mental leaf task with an observable leaf task is a single action which can be observed in turn and, consequently, can be assessed.

Take for example two leaf tasks of traffic control: “alter plan in memory” and “set deviating route”. Suppose a traffic controller points out an irregularity: a train arrives too late. The controller changes the work plan in his or her memory and subsequently sets the deviating route. Only one action is visible, making it necessary to combine the two leaf tasks in one action: “set route irregularities”

A behavioral view on the tree should comprise the conditions and the events which activate specific actions. This is very important in process control tasks: an event —like a valve out-of-order— can change the task load immensely. A list of such events may provide a nice overview of risks for overload.

Stage II: Time-Line Analysis

After describing the task properly, it then has to be assessed on the basis of the four guidelines set out in Figure 3.1. For this purpose, the process of task execution has to be analyzed. Firstly, the actions are established in an action chart for a number of scenario’s (i.e., actual task performances or task envisionments). Figure 3.3 shows an example of such a chart for one scenario with five actions of a railway traffic controller. Secondly, for a specific job the data of the action charts are summarized, if necessary standards for the first two guidelines are derived, and the summary statistics are compared to these standards. Thirdly, it is checked whether the last two standards are violated, that is, whether continuous skill-based actions or momentary overloading are present in the action charts.

Guidelines I and II. The first two guidelines are concerned with the total number of actions and the ratio between knowledge- and rule-based actions. These two guidelines have to be regarded collectively. When a lot of time is available, it may not be a problem to accomplish a difficult task, while a simple task may be boring. When little time is available, accomplishing a simple task is no problem while a difficult task may be difficult to achieve. In other words, the more actions to be executed in a period, the less knowledge-based actions are preferable. According to this view, the upper and lower limits of acceptable values for the number of actions and the ratio between knowledge- and rule-based actions are descending lines in a two-dimensional space with

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1 If the two leaf tasks are performed by two different persons, they may be described as separate actions. The action “alter plan in memory” will be visible because it must be communicated to the person that will set a deviating route.
on the x-axis the number of actions and on the y-axis the ratio. Figure 3.4 shows such a space in which the grey area defines a standard. Above the upper line task load is too high (job Y); below the bottom line task load is too low (job X).

There are no fixed values for the first two guidelines which generally apply. Therefore, the establishment of a standard is a component of the CTL-analysis. For each scenario, average task load is assessed as too low, too high, or just fine (temporary peaks in load will be analyzed later). Performance, subjective, and physiological measurements can be used for this (O’Donnell et al., 1986; Wierwille & Eggemeier, 1993). Each scenario can be positioned in the two-dimensional space just described. The scenarios with a good task load show the area in which task load is fine. This area is the standard for the total number of actions and the ratio between knowledge- and rule-based actions. The standard is formulated in terms of task characteristics, so that measures to counter loading problems can be derived. Further, the standard can be used to assess other workplaces and compare workplaces.

**Guideline III.** The third guideline states that no long-term, continuous execution of one type of action may occur. A known example of such an action in process control tasks is monitoring. In an action chart such long-term actions are simple to note (see Figure 3.3).

**Guideline IV.** According to the fourth guideline the task performance is not optimal when there is momentary overloading. With momentary overloading the proportion of knowledge-based actions rises rapidly in a short period of time. The task performance can, in such situations, deteriorate considerably, because there is an accumulation of errors. This is a major risk if errors result in high costs or safety incidents. An action chart conveys such risks (see Figure 3.3).
**Stage III: Adjusting the Task**

Hierarchical task modeling can be used for the analysis of current work and the design of work. In the first stage of the CTL-analysis a task model was created following this technique. If problems are identified in the second stage, this model is modified to overcome these problems in the current third stage. Four problems can occur: under-loading, overloading, continuous execution of one action and momentary overloading.

The first two problems are conveyed in Figure 3.4. Job X in Figure 3.4 is under-loaded and, consequently, should be extended with tasks and/or should be enriched with more complex tasks. This may cause an increase in the risk of momentary overloading. Therefore, in process control the job can often be best enriched with tasks which can be performed at any time of the day, like maintenance tasks (the task model is extended with such tasks). In normal circumstances process operators perform these tasks together with the “old” process control tasks, if overloading threatens then the maintenance tasks are left aside.

Job Y in Figure 3.4 is overloaded and, consequently, should be slimed down. The obvious measures are diminishing the mean number of tasks allocated to job Y in a certain period and/or to replace some complex tasks by simple tasks allocated to job Y. These measures involve that other persons take over tasks or that some tasks are automated.

Thus far, adjustments are proposed with respect to the static task structure. The last two problems, continuous execution of one action and momentary overloading, appear in the process of task execution (i.e., in the action chart). These dynamic effects have to be countered by changes in this process. Continuous action execution can, for example be prevented by interleaving between actions or exchanging tasks with a colleague during task execution. There are three possibilities for reducing the risk of momentary overloading. First of all, the risk is less with a dynamic task division such as when extra employees can be allocated to the current demanding task. A second possibility is that the computer provides support to the task performer in situations of momentary overloading (see, for example, Rouse, 1988). Thirdly, the number of system modules to be controlled by a process operator can be made to be dependent on the situation. In a high task load situation the number of modules can be reduced.

Figure 3.5 provides an overview of the CTL-analysis. The next section will present an application of this method to the task of railway traffic controllers.

### 3.4 CTL-Analysis in Railway Traffic Control

This section presents the first test of the CTL-analysis and the utility of its results for the Netherlands Railways. The traffic controllers of the Netherlands Railways fulfill an important role in ensuring the safe transportation of passengers and goods: they decide on which tracks the trains will travel and inform personnel and passengers about the present route of the trains. This task has changed vastly in recent times and is still changing. The number of trains a traffic controller has to deal with is increasing, the speed of these trains will be higher, the increasing number of activities to the railway system invokes more traffic variations, and more and more use is being made of advanced information technology (Lenior, 1993).

The “old” method used by Netherlands Railways for the assessment of task load no longer seems to be appropriate in these circumstances. This method is based upon the previous traffic control task which, for the most part, consisted of physical components, such as the hand setting...
### I. Hierarchical Task Modeling

- task allocation
- task breakdown per job
- behavioral view

### II. Time-Line Analysis

- collect data for several task scenarios
- construct action charts
- calculate summary statistics for the charts
- test the statistics for guidelines I and II
- test the action charts for guidelines III and IV

### III. Adjusting the Task

- extend or slim down the job
- enable interleaving, exchanging and re-allocating of tasks
- design computer support and adaptive size of system to be controlled

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**FIGURE 3.5: The Cognitive Task Load Analysis.**

of points. It does not take into consideration possible differences in task complexity and hardly assesses the cognitive processes involved in the present traffic control task. Therefore, we have tried out the CTL-analysis on this task. Is such an analysis possible and does this lead to better results than the “old” method?

This section presents the application of the CTL-analysis according to the division of the last section. Section 3.5 compares the results with the results of an application of the “old” method.

**Stage I: Hierarchical Task Modeling**

*Task Allocation.* The traffic control task consists mainly of three components: (1) deal with irregularities, (2) carry out the work plan and (3) provide information to the passengers (see Figure 3.2). At the various posts the division of these tasks among persons or jobs differs. In a quiet post the traffic controller can be responsible for all three tasks. In busier posts the task “inform passengers” can be assigned to a separate job and an assistant controller may possibly carry out the task “carry out work plan”. Other combinations also occur within the railways. However, all task allocations to persons can be designated within Figure 3.2.

*Task Breakdown per Job.* Figure 3.6 shows the information used and produced in performing the three subtasks shown in Figure 3.2. Using Figure 3.6, we can explain what the system (the “machine”) does and what the traffic controller does. Appendix A contains the full task breakdown.

The subtask “carry out work plan” is performed by the traffic controller and the system. The
process information is provided by the system and sometimes partly by others. On the basis of this information, and the work plan, the traffic controller decides to change the setting of points and signals on the railway yard. The system checks whether the desired settings are possible and—if possible—the system then sets the elements concerned in the correct position.

The subtask “deal with irregularities” is carried out as follows. On the basis of the process information and the work plan the traffic controller may adjust the work plan (by making notes in the work plan or change the plan in his or her memory) and inform personnel where necessary (e.g., by drawing up an order or by telephoning maintenance engineers). Note that the “cognitive object” memory is needed to describe planning adjustments in the memory of the traffic controller, for example, when a train is delayed.

The subtask “inform passengers” is carried out with special information boards which are sited on every platform and the public address system. To set up the information in these information boards the system has three possibilities: automatic, semi-automatic and manual. In the automatic position, the system automatically provides the entire information according to the time-table; in the semi-automatic position, the system suggests offering information according to the time-table and the traffic controller can alter this proposal on the basis of the process information; in manual position the controller types in the whole message.

**Behavioral View.** After the construction of the static hierarchical task model, leaf tasks were linked to actions which are observable in the process of task execution. This proved to be relatively easy: most leaf tasks are observable actions and the other leaf tasks can easily be combined in such an action. Figure 3.3 shows a subset of five actions: set route irregularities, prevent operation, set normal route, operate information board, and monitor. The first action is a combination of the leaf tasks “alter plan in memory” and “set deviating route” (see last section); the other four actions are leaf tasks in the tree (see appendix A).

The traffic controller performs actions if events occur (the events are part of the process information). He or she can distinguish between events that occur according to the work plan and events which deviate from this (i.e., irregularities). Examples of the first type of event are the arrival and departure of a train on time; examples of irregularities are a train passing a red signal, points going out-of-order and the message that an extra train will be coming. A wall panel shows train movements directly to the traffic controller; events which relate to objects in the infrastructure—like a malfunction in a set of points—are shown indirectly by the system, which is to say that the traffic controller can find out that an event has occurred if he or she operates the
affected object.

In interviews with experts, examples of task executions were discussed referring to, among other things, the framework of Rasmussen. Experts were able to describe their tasks in terms of rule- and knowledge-based actions. Dealing with trains which are traveling according to plan is performed mainly at the rule-based level. Traffic controllers have much experience with this task which is relatively simple, that is, which can be performed according to a set of predefined rules. A large part of the subtask “carry out work plan” is, for example, performed according to rules of the form if train T arrives at position P at time T then set route R. The extra tasks involved in dealing with irregularities, such as amending the work plan, are performed mainly at the knowledge-based level. Traffic controllers have less experience with this subtask which is generally more complicated than dealing with trains that run on time. Irregularities are often accompanied with uncertainties such as the cause of the irregularity and the duration of a malfunction. For specific situations a solution have to be planned, such as the planning of train routes when a defect train unit blocks a part of the rail yard.

Dealing with irregularities is not only relatively complex, but also involves more actions. The increase in actions occurs through the operation of information boards on the platform and the setting of routes. In the case of severe irregularities the system will, in the “automatic” and “semi-automatic” positions, provide incorrect passenger information and the information will have to be manually generated (these three control positions have been described earlier). Irregularities can be accompanied by concentrations of trains, whereby traffic controllers must use a strategy for the setting of routes which involves a greater number of actions. They can no longer set long stretches of route but guide the trains from track to next track until the desired track is reached.

Stage II: Time-Line Analysis

Sampling of Observation Periods. To investigate whether the proposed time-line analysis can be successfully applied, scenario’s of one hour were selected for workplaces with deviating task demands (see Table 3.4). First, the sample includes three different task allocations. Second, the scenario’s represent extremes in the traffic conditions. There are great variations in the number of trains which have to be dealt with by each selected traffic control post. Further, observations were done during busy (peak) periods and quiet (off-peak) periods. In one post, Roosendaal, only one observation period was carried out, because the task demands hardly vary in this small post with very little traffic. In Utrecht the most observations were carried out, because in this post task demands vary most. In total 11 systematic observations, each of one hour in length, were carried out. The observed traffic controllers had experience in the traffic control at the specific post.

Data Collection. In each scenario, the task execution of one traffic controller was observed by a task analyst and was also recorded on video. The traffic controller thought aloud while carrying out the task. To acquire an indication of task load the task analyst looked at the performance during the observation and interviewed the controller afterwards. For performance it was noticed whether large traffic delays developed in the scenario as indications of overload. In the interview, the traffic controller was asked to indicate the subjective effort invested in the scenario. Further, it was asked whether the observation fairly represented the traffic control as it usually takes place at that time and place.

Action Charts and Summary Statistics. When the video was viewed, the actions were placed into an action chart (see Figure 3.3). The five actions in Figure 3.3 have been explained above. In the first stage of the method, the behavioral view on the task conveyed the distinction between task
performance in a normal situation and a situation with irregularities. In the first situation traffic controllers work according to “pre-defined” procedures, whereas they have to plan procedures in the second situation. In correspondence to this distinction, the action chart distinguishes rule- and knowledge-based actions. Table 3.5 presents a summary of the action charts. At this phase of the analysis, the summary statistics and action charts can be evaluated with respect to the four guidelines.

Guidelines I and II. The summary statistics for knowledge- and rule-based actions were used for the assessment of the first two guidelines. For each scenario the number of actions and the ratio between knowledge- and rule-based actions were calculated (see Table 3.5), so that it could be positioned in Figure 3.7.

Setting Up a Standard. Establishing a standard for task load requires the commitment of the parties concerned in the organization. However, task load is a sore point in work analyses taking the interests of personnel and may be, among other things, a political issue. Trying to
set up a standard is a delicate matter and can hinder the collaboration of specific parties in the investigation. Therefore, we restrict ourselves to show how it can be established and to convey the value of it.

For each scenario the task load was assessed based on two criteria: traffic controllers’ performance and subjective effort (see above). Except for observation 8 performance was assessed to be without problems (i.e., no large traffic delays developed). However, in the interviews task load proved to be experienced as non-optimal. In Eindhoven and Roosendaal the task load was experienced as low for all scenario’s; in Utrecht scenario 6 and 10 were acceptable, but for the rest the task load was too high in this post.

The observations seem to be reasonably representative for the traffic control task at the three workplaces. All those being observed indicated that the observation periods were representative of the normal task performance except for observation 8 in which the traffic controller on duty indicated that the effort was higher than normal (see below under momentary overloading). However, the number of observations was too small to establish a standard for the railway traffic control task. The 11 observations insufficiently embody a standard area such as presented in Figure 3.4; only observation 6 and 10 fall inside such a standard.

More data is required to investigate the value of a standard. Therefore, the results of other task analyses at traffic control posts were reanalyzed in such a way that the results could be put in Figure 3.7. The subtasks of the scenarios concerned were divided in rule- and knowledge-based actions and the summary statistics were calculated\(^2\). Load evaluations were available (expert judgments), so that they could contribute to the setting of a standard area in the figure. According

\(\text{FIGURE 3.7: The number of actions and the ratio between knowledge- and rule-based actions for the 11 scenario’s. The letters E, R and U show the means of the jobs at Eindhoven, Roosendaal and Utrecht. The closed area represents a provisional standard.}\)
Harmonizing Tasks to Human Knowledge and Capacities

to this provisional standard, the mean number of actions that have to be performed in one hour should lie between 60 and 100; the number of rule-based actions should be about 2 to 10 times greater than the number of knowledge-based actions. This latter ratio is only valid in those situations which meet the standard for the number of actions. In general the rule is: the lower the number of actions, the greater the percentage of knowledge-based actions has to be and vice versa. If there are 60 actions the knowledge/rule ratio should be about .5, whilst if there are 100 actions the ratio should be about .1 (see Figure 3.7).

### TABLE 3.6: The task performance in the three traffic control posts in terms of the four guidelines.

<table>
<thead>
<tr>
<th>Post</th>
<th>Mean actions/hour</th>
<th>Average ratio knowledge/rule</th>
<th>Continuous actions</th>
<th>Momentary overloading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eindhoven</td>
<td>15</td>
<td>.40</td>
<td>monitoring</td>
<td>none</td>
</tr>
<tr>
<td>Roosendaal</td>
<td>17</td>
<td>.70</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Utrecht</td>
<td>108</td>
<td>.47</td>
<td>monitoring</td>
<td>1 period</td>
</tr>
</tbody>
</table>

Assessing Jobs. The second and third column of Table 3.6 present the statistics referring to the first two guidelines. In Eindhoven and Roosendaal the traffic controllers are, according to the standard, under-loaded (job E and R in Figure 3.7); they have on the whole too little to do. In Utrecht task load is too high (job U in Figure 3.7). The proportion of knowledge-based actions may appear to be quite high. This can be explained as follows. In Utrecht it is so busy that the traffic controllers have a strategy in which no long stretches of track are set, but which brings the trains “bit by bit” towards the desired destination. Such a strategy looks like “hill climbing”: they choose those actions which brings them ever closer to the most ideal solution. In Eindhoven the traffic controller carries out only the task of dealing with irregularities (see Figure 3.2): this is a task which in principle has many knowledge-based actions. In Roosendaal, there was only one observation period. During this observation period an irregularity appeared, in which the traffic controller had to deal with a defect signal. The total number of actions performed by this traffic controller was very low, so that dealing with this irregularity had a major impact on the average ratio between knowledge- and rule-based actions.

Guideline III. The action charts revealed that monitoring is a long-term, continuous action in Utrecht and Eindhoven. In these two posts routes regularly have to be set. Between and during this route setting, the operation information must be almost continuously inspected. In Roosendaal it is quiet and for each train a long section of route can be set which covers the whole yard. If this has been done then there is no need to continuously inspect the operation information: the system provides an auditory signal if a train approaches the yard.

Guideline IV. Although momentary overloading was conveyed only once in the action charts, it proved to be an important problem. In observation 8 the traffic controller had to deal with 47 trains within a period of one hour during the observation period in question. In the last half hour a number of irregularities arose: a delayed train and a set of points which became non-operational. Figure 3.8 shows the number of rule-based and knowledge-based actions per quarter of an hour.

The number of actions per 15 minutes appears to vary greatly (between 28 and 45). This number accords with the number of trains that have to be dealt with: there is a peak in the first
quarter and a peak in the third quarter (this is the result of many trains running a half-hourly service).

Accordingly, it is noticeable that there are relatively more knowledge-based actions in the second half hour when irregularities occur. If one looked at the number of actions, one would find no difference between the two situations. The task load in the second situation is however considerably higher. The next part of this section discusses how the traffic controller may deal with such situations which are often difficult to predict.

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Stage III: Adjusting the Task

In the last stage, the CTL-analysis conveyed some mismatches between the task demands and the controllers’ capacities: under-load, overload, continuous action execution, and momentary overloading. The following adjustments of the task model for the three control posts are possible to improve the task load of traffic controllers. In Roosendaal the task load is very low, because there are few actions to be performed. Even during irregularities overloading will rarely occur, because only a very small number of trains pass this post. The task could be extended with work preparation, organizational tasks, and the control of (a part of) another railway-yard. In Eindhoven the task load is also low. Here the task allocation could be adjusted: the traffic controller —like in Roosendaal— could also be responsible for carrying out the work plan and informing the passengers in addition to dealing with the irregularities. The traffic controller in Utrecht carries the heaviest load. This post is very busy and irregularities have widespread effects. Possible solutions may be found in providing more breaks, the use of temporary staff, and reducing the control area of the traffic controller during irregularities. Dealing with irregularities is a demanding subtask compelling knowledge-based actions. Computer support for this subtask may be very beneficial for busy control posts such as Utrecht (this will be investigated in chapter 6).

3.5 Comparing to the “Old” Method

The task load of the 11 scenarios was also assessed with the “old”, non-cognitive method of the Netherlands Railways to test whether the cognitive task load analysis produces better results. The “old” method divides the traffic control task into six types of observable actions (see Table 3.7). For an eight-hour shift three standards have been established based on the judgment of ergonomics
experts: (1) the number of actions per hour, with the exception of monitoring, is less than 200, (2) the measured action time is no more than half the shift time and (3) for more than 25% of the shift time the traffic controller does not perform any action for more than a minute (is at rest) (Rookmaaker, 1985).

<table>
<thead>
<tr>
<th>Action type</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel operation.</td>
<td>Operating points or signals with push-buttons.</td>
</tr>
<tr>
<td>Operating public address system</td>
<td>Indicating delays.</td>
</tr>
<tr>
<td>Operating public address system</td>
<td>Operating public address system</td>
</tr>
<tr>
<td>or information board.</td>
<td>Indicating delays.</td>
</tr>
<tr>
<td>Monitoring panel.</td>
<td>Watching points positions and track occupation.</td>
</tr>
<tr>
<td>Consultation about the work.</td>
<td>Discuss solutions with colleagues.</td>
</tr>
<tr>
<td>Administration.</td>
<td>Establishing changes in the work plan.</td>
</tr>
<tr>
<td>Telecommunications.</td>
<td>Telephone conversation with train drivers.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Post</th>
<th>Actions per hour</th>
<th>(t_a/t_{total}) (&lt;.200)</th>
<th>(t_r/t_{total}) (&lt;.5)</th>
<th>(t_r/t_{total}) (&gt;.25)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eindhoven</td>
<td>15</td>
<td>.78</td>
<td>.29</td>
<td></td>
</tr>
<tr>
<td>Roosendaal</td>
<td>17</td>
<td>.08</td>
<td>.95</td>
<td></td>
</tr>
<tr>
<td>Utrecht</td>
<td>108</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

For the 11 scenario’s, the actions and action time were counted and, subsequently, these statistics were compared to the three standards. Table 3.8 shows the statistics for the three control posts. The tasks in all posts satisfy the first standard: the number of actions per hour, with the exception of monitoring, is less than 200. In Eindhoven and Utrecht the task deviates from the second standard: the action time is more than half the shift time in these posts. Monitoring causes this deviation. For the same reason the third standard is violated in Utrecht: there is no time of rest in this post. In sum, the “old” method conveys a monitoring problem in Eindhoven and Utrecht and conveys no problems in Roosendaal.

In comparison with this result, the CTL-analysis conveys more problems. First, it points out situations of under-load. Second, it presumes specific cognitive processes “behind the observable actions” and, consequently, conveys problems with respect to these processes. In this way, the influence of irregularities on task load has been pointed out for traffic controllers. The task load can be split into two components: loading during normal circumstances and during disrupted circumstances. Task load during a disrupted situation is much higher, because in such situations problems concerned with track use and the like have to be solved.

Unlike in the “old” method, in the CTL-analysis the derivation of measures to improve task load is rather straightforward. Measures are changes in the hierarchical task model, such as adjustments in the task allocations or the design of computer support for a part of the task.
3.6 Conclusions

This chapter presented the development of a method to analyze cognitive task load and an exploration of its applicability and utility for railway traffic control. Sections 3.2 and 3.3 showed the integration of a selected set of principles of human task performance into current task analysis techniques to enable the assessment of cognitive demands of complex work. Whereas in ergonomics absolute standards are often used to assess working conditions (e.g., the height of a chair or letter size on a computer display), the CTL-analysis comprises guidelines which provide mainly relative values. Absolute values that stipulate acceptable versus unacceptable levels of workload do not generally exist and do not appear probable in the foreseeable future (Wierwille & Eggemeier, 1993). To overcome this problem, the CTL-analysis follows a rather new approach by encompassing of a procedure to establish acceptable values for a specific job.

Section 3.4 showed that the CTL-analysis can be applied for railway traffic control: a hierarchical task model was constructed, a time-line analysis was applied and the results were compared to the guidelines, and proposals for task adjustments were formulated. Furthermore, this method proved to produce better results than the “old” method of the Netherlands Railways. Whereas the “old” method only pointed out monitoring problems, the CTL-analysis detected four problems—under-load, overload, continuous action execution, and momentary overload—and produced proposals to improve the task load.

In section 3.1, it was argued that traditional task analysis techniques are deficient in assessing cognitive task demands and, consequently, do insufficiently address the complexity of work. The CTL-analysis showed the importance of task complexity: the sudden increase in task load in scenario 8 was caused by an increase in knowledge-based actions, whilst the total number of actions did not increase (Figure 3.8). Next to the number of trains, the occurrence of irregularities proved to be an important factor of workload. This effect was not noticed with the “old” method.

Taken together, the conclusions of this investigation are: (1) the selected knowledge about cognitive processes can be integrated into current task analysis techniques, (2) task load can be assessed using guidelines with relative values, (3) the CTL-analysis can be applied in railway traffic control, and (4) the CTL-analysis is more useful than the “old” non-cognitive method for load assessment of the Netherlands Railways. It seems worthwhile to continue this research to acquire a solid, empirical foundation of the method. The next section discusses some important issues for future research.

3.7 Discussion

Rasmussen’s (1986) and Reason’s (1990) framework was developed to analyze errors in process control tasks, but also seems to be suitable to assess the complexity of tasks. In our investigation this framework could be used in interviews with traffic controllers to assign actions to various levels of information processing. The question still remains whether other task analysts would come to exactly the same pattern of assignment.

A cognitive task analysis can be used for a broad spectrum of objectives. For different purposes, different cognitive task analyses are applicable. The method presented here is aiming at the allocation of a set of tasks to computer users which correspond to their capacities. It has to be realized that the scope of the analysis is limited to a selected set of capacities (see section 3.2). The cognitive task load analysis can be of special value as part of a broad workload assessment. Research in air traffic control indicates that the number of aircraft is the most important factor of
workload (Hurst & Rose, 1978; Costa, 1993). This research focuses on stress, i.e. the discrepancies between the environment and the person, whereas our research focuses on cognitive load, i.e. the discrepancies between the task demands and the processing capacities required for the execution of the task (Gaillard, 1993). A CTL-analysis may complement stress research by assessing cognitive load and may for example, consequently, convey effects of irregularities on workload in air traffic control. In railway traffic control such effects are apparent.

In the CTL-analysis, the task model guides the proposition of measures: the model is the object to be redesigned in such a way that the problems pointed out are diminished. This approach fits well to current design approaches for software systems using iterative hierarchical task modeling (Yourdon, 1989; Rumbaugh et al., 1991). In future the task load assessment may be part of the redesign of the man-machine system. This requires that the present situation can be abstracted to a future system. Up to a certain level the hierarchical task model will remain the same, like the model in Figure 3.2. The events described —in as much as they are not caused by the “machine” itself— will also be dealt with by the new man-machine system. At the level of the division of tasks between man and the machine there may well be changes. For the new design, scenarios can be suggested and, subsequently, the task load can be assessed. The scenarios must, in any case, include important irregularities. To establish standards for an optimal task load, “projective task load” techniques can be useful (Vidulich et al., 1991). With such techniques, subject matter experts can compare task designs (i.e., proposed task models) and choose the design with the best task load.

Task analysis involves gathering, transforming, and summarizing of a lot of data. The computer can be a valuable tool for such activities. For the cognitive task load analysis of this chapter, such a tool would make it possible to do the analysis in a relatively short period and possibly to redo some parts of it when the task is going to change (e.g., for redesign).

Ergonomics should not only provide warnings and categorizations of human problems in automated workplaces, but also develop solutions. Information technology brings about new possibilities for making human involvement more effective. Future research should be directed towards these possibilities next to the problems of automation. In railway traffic control, the risk of overload caused by irregularities cannot be diminished completely by a re-allocation of tasks and, therefore, it is proposed to design computer support for this subtask. Chapter 6 focuses on such a possibility: the design of an aiding interface which provides the traffic controller rule-based advice when irregularities occur. With such advice, the traffic controller may deal with irregularities mainly at the rule-based level which requires less effort than the current knowledge-based performance.

The following chapters will first focus on a more apparent objective of computer advice: the compensation of knowledge deficiencies of computer users. Then —in chapter 6— the compensation of knowledge and capacity deficiencies will be investigated.

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