Overview

In Chapter 3, much of the focus of our discussion was on how people attended to or perceived two (or more) channels of perceptual information at once, that is, divided attention. We emphasized the concept of proximity to account for much of that success, and also the concept of an optimal allocation of the attentional spotlight, to effectively select from among multiple channels. In subsequent chapters, we discussed further stages of information processing related to cognition and working memory, and response selection and execution. Now it is appropriate to reexamine the issue of divided attention, but this time from the perspective of dividing attention between tasks, and not just between perceptual channels. The difference is that a task may encompass multiple stages of information processing, and also will be defined by a specific goal (which can in turn be characterized by a performance metric). Thus, for example, the goal of the task of driving is to keep the car centered in the lane at a specified speed without collision. Several perceptual channels may be used to achieve that goal, and the stages of response selection and execution are critical, as well as that of perception.

Examples of divided attention between tasks are plentiful. Our unfortunate van driver who was trying to diagnose the problem of his automated dispatcher while driving is just one such example. Another is when you rehearse the phone number of the pizza place while listening to your companion give you a pizza topping request. Still another is remembering the message on one computer screen while you go through the actions necessary to pull up a second screen. Also, consider the point guard on the basketball team who deftly controls her dribble around a defender while monitoring for the center to cut to the open spot under the basket.

The above examples have ranged from major failures of divided attention (the unfortunate van driver) to brilliant successes, with varying degrees of success in be-
tween. In the first half of this chapter, we focus on four classes of mechanisms that account for variability in the success of divided attention or time-sharing. Then we turn to a discussion of mental workload, one of the most important human factors issues in the study of divided attention. In our discussion of divided attention, we offer the baseline of single task performance. Two tasks performed concurrently (time-shared) as well as each would be performed under single task conditions defines perfect time-sharing or perfect parallel processing. When one or the other drops below its baseline, we say there is a dual task decrement or dual task interference. Our emphasis is on understanding the four processing mechanisms—resource demand, switching and allocation, structure, and confusion—that account for the failures and successes of time-sharing.

We should note that these four mechanisms are by no means mutually exclusive, and we have seen some examples of their different manifestations in earlier chapters of this book. However, it is also true that each has been associated with different theoretical positions. Indeed, one preliminary note should be made. The concept of "attention" has sometimes been considered to be indivisible and, hence, "divided attention" an inherent contradiction. In our writing, we reject this position, but for those who may be uncomfortable, we offer the alternative phrase of "concurrent processing" or "time-sharing" as a means of describing an operator doing two things at once (independently of where attention may be focused).

**MECHANISMS OF TIME-SHARING**

**Automaticity and Resources**

In Chapters 6 and 7, we learned of the distinction between automatic and controlled processes in perception (Schneider & Shiffrin, 1977). Automatic processes were formed on the basis of a consistent mapping between stimulus and some further categorization, and they were rapid, accurate, and relatively resource free. Such a mechanism explains the automatic processing of familiar perceptual stimuli such as letters (LaBerge, 1973), consistently assigned targets (Schneider & Fisk, 1982; Schneider & Shiffrin, 1977), and repeated sequences of stimuli (Bahrick, Noble, & Fitts, 1954; Bahrick & Shelly, 1958), as well as the automatic performance of habitual or highly practiced motor acts such as signing one's own name or shooting a jump shot. When describing the response end of processing, this automaticity of performance is referred as the motor program (Keele, 1973; Summers, 1989), as discussed in Chapter 10. Thus it is not surprising that automatic processing can be readily and efficiently timeshared with other more demanding tasks (Schneider & Fisk, 1982).

The concept of automaticity can be applied to a wide range of activities. Walking is a nearly automatic activity for most of us (as long as the ground—the stimulus—that supports walking is consistent and predictable), so we can easily and effortlessly walk and do other tasks with perfect time-sharing. Even if the surface is not perfectly flat, so that walking is a little more difficult (is no longer entirely automatic), we can still perfectly time-share. However, we have now brought two other factors into the equation of predicting multiple-task performance: effort and difficulty.
The factors of effort and difficulty suggest that automaticity is not really an all or none phenomenon, but rather can be thought of as a continuum which can be related, inversely, to the mental resources demanded by a task (Kahneman, 1973). Thus, we may speak of a task demanding more resources (because it is more difficult), in which case its performance is likely to decline in dual task circumstances. Alternatively, we may speak of more resources (effort) being allocated to a task, in which case its performance will be likely to improve. A useful framework for thinking about this continuum is the performance resource function, or PRF (Norman & Bobrow, 1975), an example of which is shown in Figure 11.1. Single-task performance occurs when all resources are invested in the task (point 1 on curve B) and is the best that can be obtained. Diverting a large amount of resources away from the task shown in the top curve to a concurrent task will depress performance accordingly, as indicated by point 2. As more resources are then reinvested back into the task, performance will improve up to point 3, at which no further change in performance is possible. To the right of point 3, the task is said to be data-linked (limited by the quality of data, not by the resources invested). Data limits may occur at any level of performance. Remembering a two-digit number is data-limited, since perfect performance can be obtained with few resources and further effort will lead to no improvement.

Data limits also occur in vigilance with low-intensity signals, or in understanding a conversation in a language with which you are only faintly familiar. In both cases, no matter how hard you try (how much effort you invest), perfect performance is impossible, and beyond a particular level, performance gains will not be realized with more

![Figure 11.1](image)
effort. When performance does change with added or depleted resources, the task is said to be resource-limited, the region to the left of point 3 on curve B in Figure 11.1.

**Time-Sharing and the PRF** If all resources are presumed to come from the same source (an issue we address later in the chapter), then the interference between two tasks is determined by the form of the two PRFs. In Figure 11.2a, the PRF for task B is plotted backward so that a given vertical slice through both functions will represent a single policy of allocating $X$ percent resources to task A and $(100 - X)$ percent to task B. Maximum single-task performance on each task is given by 100 percent resource allocation. If resources are divided between tasks, performance must drop off on one or both unless both are data-limited, as in Figure 11.2b. In this case, the allocation of 40 percent resources to task A and 60 percent to task B will provide perfect time-sharing. That is, both tasks performed concurrently can be done as well as either task performed alone.

**Automaticity and Difficulty** The effects of both practice and task difficulty can be easily represented by the resource metaphor. Figure 11.1 shows the PRF represented by two tasks, A and B. Task B demands fewer resources to reach performance levels that are equivalent to A. Task B also contains a greater data-limited region. Task B then differs from A by being of lesser difficulty or having received more practice (being more automatic). Note that task B may not necessarily be performed better than task A if full resources are invested into A but can simply be performed at that level with more spare

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**Figure 11.2** Performance resource functions (PRFs) of two time-shared tasks. (a) Two resource-limited tasks with 50/50 allocation policy. (b) Two data-limited tasks with 40/60 allocation policy, demonstrating perfect time-sharing.
resources (i.e., at point C). Hence, task B will be less disrupted by diverting resources from its performance than will task A. We saw in Chapters 3 and 6 that the best way to produce this automaticity is through repeated practice on tasks with consistently mapped characteristics (Schneider & Shiffrin, 1977).

The implication of the difference between PRFs such as those shown in Figure 11.1 is that the extent of differences between two tasks or two situations may not be appreciated by examining the performance on each task alone. Only when the primary task (i.e., the task of interest) is time-shared with a concurrent task will the differences be realized. When the primary task is emphasized in a dual-task situation, the concurrent task is called a secondary task. Thus; for example, Bahrick, Noble, and Fitts (1954) employed the secondary task to index differences in learning of a perceptual-motor task that were not revealed by primary-task performance. Dornic (1980) compared comprehension of first and second languages by bilingual speakers and observed differences in the secondary tasks and none in the primary. The use of secondary tasks as one means to assess mental workload is considered in greater detail later in this chapter.

**Performance Strategies and the PRF** The concept of the PRF—the relationship between effort and performance—has been encountered before in the discussion of decision-making heuristics in Chapter 8. Heuristics are seen as mental shortcuts that can provide reasonably good performance without the investment of too much effort. For example, in choosing between several options, a heuristic like "elimination by aspects"—might show a PRF such as that shown by the solid line in Figure 11.3. An optimal compensatory strategy, in which all attributes of all options are considered, might show a PRF such as that shown by the dashed line. Which strategy will be chosen? The answer

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**Figure 11.3** Relationship between heuristic and optimal strategies for performing the same task, as represented in the PRF space.
is given by considering the role of utility in relation to effort and performance. Assuming that there is a positive utility to good performance, but also a positive utility to conserving effort (prolonged investment of high effort is fatiguing), we may think of the PRF space as having a “good” region (low effort, high performance at the upper left) and a “bad” region (high effort, low performance in the lower right). Navon and Gopher (1979) speak of lines of constant utility radiating from the origin of the PRF (these are the light lines shown in the figure). Accordingly, people will choose to operate at points farther to the upper left in the PRF space. As we can clearly see in Figure 11.3, the heuristic PRF has a region farther to the upper left than does the optimal strategy PRF—which can explain why people will choose to use heuristics rather than optimal strategies.

As we noted in Chapter 8, some models of decision making have directly incorporated concepts of effort into their computations (Bettman, Johnson, & Payne, 1990; Payne, Bettman & Johnson, 1993). But the utility of the trade-off between performance and effort is also relevant to other domains as well. For example, Soede (1980) and Shingledecker (1989) discuss the role of effort in the use of prosthetic devices for people with disabilities. Very effective devices (yielding high performance) may not be chosen because of their high demand for effort. The trade-off is equally relevant for understanding why certain powerful but complex features in computing systems are not used. Indeed, the rationale behind many of the direct manipulation techniques discussed in Chapter 5 was not that they offered greater potential performance levels but rather that their performance could be obtained with reduced effort. The issue of how to measure the effort required for task performance—the measurement of mental workload—is discussed later in this chapter.

In summary, investing effort or resources into a task of constant difficulty will improve its performance if the task is resource limited. Increasing the difficulty (resource demand) of a task will decrease performance unless more resources are supplied to compensate. In a single-task situation, the added resource investment will generally produce a cost in terms of experienced effort (with negative utility). In a dual-task situation, added resource investment into one task will produce a decrement in the concurrent task, unless the latter is data limited or automated.

### Resource Allocation and Switching: Strategic Control

**Allocation Skill** We have discussed the importance of allocating attention or resources between different channels or tasks in at least two different context in previous chapters. In Chapter 3, we considered the optimal deployment of selective attention, in which the operator typically allocated visual attention (foveal vision) to a channel, characterized by its information content and value. In Chapter 8, we spoke of this same optimal deployment across decision-making cues, and also the choice of allocating or conserving effort between different decision strategies, based on anticipated accuracy (Fennema & Kleinmuntz, 1995).

What is apparent from these and other discussions (Gopher, 1991) is that vast differences in the apparent success of time-sharing, or doing multiple activities, can be achieved via the strategic allocation of resources between tasks. Our example at the beginning of the textbook illustrates poor resource allocation policy: The driver was attending more to the dispatcher display diagnostics and less to the roadway than was warranted. Conversely, Schneider and Fisk (1982) found that subjects could time-share
an automatic and a resource-demanding letter-detection task with perfect efficiency if they received training to allocate their resources away from the automatic task (which of course required few resources in the first place). In the absence of this training, subjects allocated resources in a nonoptimal fashion by providing more resources to the automatic task than it needed, at the expense of the resource-limited task. In the example in Figure 11.2b, this situation was as if subjects initially allocated 60 percent of the resources to A and 40 percent to B and needed to be trained to adopt the more optimal 40/60 split. This paradigm is interesting in that it shows the contributions of both single-task automaticity (for the automatic detection task) and dual-task resource-allocation training to overall time-sharing efficiency.

The learning of perceptual sampling strategies related to time-sharing was discussed in Chapter 3 in regard to the experiments performed by Senders (1964) and Sheridan (1972). The notion that strategies in allocating and switching attention contribute to improved time-sharing performance has received further support from more recent experiments. As noted in Chapter 7, Gopher, Weil, and Siegel (1989) found that training that emphasizes dynamic attention control leads to better transfer to a complex multitask video game than does training with a fixed attention allocation policy between tasks. Gopher, Weil, and Bareket (1994) observed that the training of attention allocation skills, accomplished in a video game called Space Fortress, could transfer to piloting skills in complex fighter aircraft, and indeed, such training increased the likelihood that Israeli Air Force pilots would be chosen to pursue the highest levels of fighter aircraft training. Kramer, Larrish, and Strayer (1995) found that training attention control on one pair of tasks transferred effectively to support dual-task performance on a second unrelated pair, and did so particularly for older adults who have more difficulty with time-sharing. Walker and Fisk (1995) found that an attentional training program could improve the performance of both college and professional quarterbacks in "reading the defenses".

**Optimal Allocation and Switching** Although it is clear that training can improve certain aspects of resource or attention allocation skills, existing research results are less clear about what the specific departures from optimal allocation are, and how these departures are influenced by task properties and environmental goals. Just as we specified an optimum weighting for decision cues as a function of their information value (Chapter 8), and for perceptual sampling as a function of channel bandwidth (Chapter 3), so here it is possible to prescribe an optimal allocation schedule to tasks as a function of their importance (or their cost of non- or inaccurate completion). We can then ask how much of an influence task importance has on resource allocation or task management, and what irrelevant or unrelated factors influence task management (and therefore might be expected to preempt the performance of important tasks if placed in conflict with it).

While there does not appear to be a great deal of research in this area, a few basic assertions regarding the relationship between optimum and actual allocation of resources to tasks can be stated with some confidence.

1. There is a cost for switching between tasks (Moray, 1986; Sheridan, 1972; Jersild, 1927; Rogers & Monsell, 1995), and so there is a tendency to continue performing a lower-priority task longer than optimal (i.e., to avoid switching) if the need to perform a task of higher priority suddenly arises. We saw this "inertia effect" with the vehicle driver at the beginning of the chapter: a failure to
switch soon enough from head-down diagnostics to head-up lane monitoring. Some literature in aviation psychology reveals the failures in task management and timely switching to high-priority tasks (Schutte & Trujillo, 1996), sometimes in ways that can lead to aircraft incidents and accidents (Chou, Madhavan, & Funk, 1996).

2. The concept of switching attention suggests a "movement metaphor" such that it should take longer to shift attention between more distant tasks than more proximate ones. This is, of course, true when attention is shifted between widely spaced visual sources (greater scanning distance imposes greater time requirements), but it does not necessarily apply for "cognitive distance" (i.e., switching between dissimilar tasks is not necessarily longer than switching between more related ones). In fact, a high degree of relatedness or similarity between old (pre-switch) and new (post-switch) activity may actually lead to interference as the new activity is undertaken.

3. Different physical or salient sensory annunciators or reminders to perform a task will be more likely to trigger a switch to that task than will less salient properties, or purely memorial representations (Wickens & Seidler, 1997). For example, when the physical nature of a stimulus uniquely defines the nature of the cognitive processing required of that stimulus, switching to that task is more rapid than if the stimulus signals ambiguously (Allport, Styles, & Hsieh, 1994).

4. In contrast to computer optimization models, people do not tend to maintain elaborate and highly optimal planning strategies for task management (Liao & Moray, 1993; Laudeman & Palmer, 1995; Raby & Wickens, 1994), such as carefully calculating the appropriate optimal sequence in which to perform tasks of differing priority. This simplification apparently results because applying such strategies themselves are a source of high cognitive workload or resource demand (Tulga & Sheridan, 1980) and, hence, would be self-defeating at the very time they might be most necessary.

5. As a correlate of item 4, people tend to be more proactive in task management when workload is modest (i.e., establishing various contingency plans for future uncertain events), and more reactive when workload becomes high (Hart & Wickens, 1990).

6. There is a good possibility that well-designed automation can provide support for people's task management skills, by monitoring their performance and providing reminders if high priority tasks are "dropped" (Funk & McCoy, 1996; Wiener & Curry, 1980; Hammer, 1999).

Summary It is important to place the first two characteristics accounting for variance in time-sharing efficiency in contrast. The characteristics of automaticity and resource demand were properties of a single task, just as relevant to single- as to dual-task performance. They could be delivered either by characteristics (difficulty) of the task itself or by the skill level (practice) of the operator. In contrast, resource allocation is and must be an emergent property of the combining of two or more tasks (or channels). One cannot speak of allocating resources or switching between a single task. Furthermore, while the first characteristic, resource demand, may sometimes be related to the skill level of the operator, but often is an intrinsic property of the task, it appears that the second
characteristic, resource allocation policy, is nearly totally related to operator skills. This distinction is important for training. As we discussed in Chapter 7, limited training time can be devoted to single-task components (part-task training) or dual-task skills (whole-task training). Only automaticity will develop in the former condition, but both automaticity and resource allocation skills may have the opportunity to develop in the latter, if care is taken to follow good training guidelines. Hence, whole-task training tends to be more effective than fractionized part-task training.

Up to now, we have not distinguished our discussion of resource allocation between a graded allocation (e.g., providing 80 percent of one's resource to task A and 20 percent to B) and a discrete or attention switching allocation (e.g., switching attention exclusively to task or channel B for two seconds out of every 10, and remaining focused exclusively on A for the remaining time). With respect to the importance of training, these two mechanisms (graded or discrete) are probably equivalent. Furthermore, if the time base of switching becomes sufficiently fine (e.g., switching 2–3 times/second), then the two are probably functionally equivalent insofar as prediction of performance is concerned. However, it is important to recognize that certain structural constraints limit the ability of the operator to engage in concurrent processing and, therefore, are more likely to force a sequential switching policy. The most obvious of these constraints is the access to foveal vision, and it is for this reason that the visual scanning measure represents such a nice index of attention allocation policy, as discussed in Chapter 3. It appears however that other structural properties in the body or brain physiology also modulate the ease of concurrent processing, and these are discussed in the following section.

Structural Factors in Time-Sharing Efficiently

In the previous two sections, we portrayed a model of resource demand and allocation that implicitly suggested that these resources were fairly well indiffereniated—that it did not matter much whether tasks were visual, auditory, spatial, or linguistic, perceptual, action-oriented. The key feature in predicting time-sharing interference was the demand for resources and the allocation policy. Yet some obvious observations inform us that other factors are at play in dictating time-sharing efficiency. As one obvious example, it is harder (and thus more dangerous) to read a book while driving than to listen to the same book on tape. The time-sharing efficiency of the two activities is drastically changed by using visual rather than auditory input channels for language processing. In this section, we consider two somewhat different but complimentary approaches to these structural effects on resource allocation: bottleneck theory and multiple resource theory.

Bottleneck Theory An understanding of the structural constraints on time sharing has emerged from the work that has been carried out in the dual stimulation or psychological refractory period paradigm discussed in Chapter 9 (Welford, 1952, 1967; Pashler, 1998; Kantowitz, 1974). Here, time sharing is challenged to its utmost as people are asked to perform two reaction-time tasks at the same time. As discussed in Chapter 9, the challenge for perfect time-sharing is essentially impossible to meet, and one RT task or the other (usually RT to the second stimulus arriving) suffers a decrement. Sometimes both RTs will be prolonged beyond their single-task baseline.
Through careful manipulation of perceptual and response demands, and the timing of the various stimulus arrivals, Pashler (1998) carefully modeled the process to confirm earlier data that the primary bottleneck in this process is at the stage of response selection (Pashler refers to this as “central processing”). That is, two independent responses, based on unpredictable stimulus input, cannot be selected at the same time; one or the other must be postponed. In contrast, however, his analysis reveals that selection of the response for one stimulus can proceed concurrently with perceptual processing of the other stimulus (Pashler, 1989) or with the execution (but not selection) of the other response. Thus, the bottleneck model suggests that the resource available for response selection must be allocated in an all or none fashion to one task or the other.

While concurrent response selection for two tasks is prohibited according to bottleneck theory, there is also ample evidence, some of it discussed in Chapter 3, that concurrent perceptual activity for two tasks can also compete. This, of course, meets with our intuition even when the structured constraints of foveal vision are not encountered: Reading and listening—two perceptual activities—cannot be perfectly time shared. Thus a more elaborated model of resources within the information processing system, shown in Figure 11.4, suggests that the resources available for perception are limited (and must sometimes be shared between channels), just as are the resources available for response selection (although Pashler’s model suggests that the latter might be even more limited and allocated on an all or none basis, rather than a graded one). But the use of separate—limited—resources for the two processes, perception and response, should avail more efficient concurrent processing when both are required, compared to the use of a single resource for two activities.

**Multiple Resources** The distinction, shown in Figure 11.4, between resources underlying perception (and working memory) and those underlying the selection of actions turns out to be only one of at least three important structural dichotomies within the human brain that can help to account for variations in time-sharing efficiency. These variations can be modeled in terms of the differences in resources supplying the two sides of the three dichotomies that are represented as a cube in Figure 11.5. In addition to the

![Image of Figure 11.4](image)

*Figure 11.4* The distinction between resources underlying perception and resources underlying the selection of actions.
Chapter 11 Attention, Time-Sharing and Workload

Figure 11.5 The proposed structure of processing resources. Operations on either side of a solid line use different resources.


stages dichotomy shown in Figure 11.4, there is evidence for differences due to auditory and visual perceptual modalities, and to spatial (analog) and verbal (linguistic) processing. Collectively, all three dimensions have been incorporated into the multiple resource model shown in Figure 11.5, which is an elaboration by Wickens (1980, 1984, 1991) of the more general concept of multiple processing resources proposed by Kantowitz and Knight (1976) and Navon and Gopher (1979). The cubelike graphical depiction in Figure 11.5 is meant to suggest that the three dimensions are somewhat independent of each other, that the vertical modality dichotomy between auditory and visual resources can only be defined for perception, but that the code distinction between verbal and spatial processes is relevant to all stages of processing. The left-right placement of the code dichotomy is intentional, suggesting that the dichotomy is often (although not invariably) associated with the left (verbal) and right (spatial) cerebral hemisphere. Finally, the stage of processing dimension is represented with only two resources rather than three, suggesting, as shown also in Figure 11.4, that perceptual and cognitive (i.e., working memory) processes demand the same resources, different from those involved in action selection and execution. As noted in Chapter 7, sensory store is relatively resource-free. In the following, we discuss evidence for each dimension in turn (in terms of evidence for better time-sharing between two levels of the dichotomy than within levels).

Stages The resources used for perceptual and working memory or cognitive activities appear to be the same, and they are functionally separate from those underlying the
selection and execution of responses. Evidence for this dichotomy is provided when the
difficulty of responding in a task is varied and this manipulation does not affect per-
formance of a concurrent task whose demands are more perceptual in nature. We have
noted already how this view is consistent with bottleneck theory, and the research of
Pashler and his colleagues (Pashler, 1998) has elegantly demonstrated the relative inde-
pendence of perceptual demand and response selection processes in concurrent RT tasks.
The stage dichotomy can be further supported by physiological evidence. In a series of
experiments by Isreal, Chesney, Wickens and Donchin (1980) and Isreal, Wickens,
Chesney, and Donchin (1980), the amplitude of the P300 component of an event-re-
lated brain potential (see Chapter 9) elicited by a series of counted tones is assumed to
reflect the investment of perceptual and cognitive processing resources, since the P300
can be elicited without requiring any overt responses. The experiments revealed that the
P300 is not sensitive to response-related manipulations of tracking difficulty but is in-
fluenced by manipulations of display load. Shallice, McLeod, and Lewis (1985) examined
dual-task performance on a series of tasks involving speech recognition (perception) and
production (response) and concluded that the resources underlying these two processes
are separate. It is also important to note as well that the stage dichotomy can be associ-
ated with different brain structures. That is, speech and motor activity tend to be con-
trolled by frontal regions in the brain (forward of the central sulcus), while perceptual
and language comprehension activity tends to be posterior of the central sulcus.

As an operational example of separate stage-defined resources, we would predict
that the added requirement for an air traffic controller to acknowledge vocally or
manually each change in aircraft state (a response demand) would not alter his or her ability to maintain an accurate mental model of the airspace (a perceptual-
cognitive demand).

Perceptual Modalities  It is apparent that we can sometimes divide attention between
the eye and ear better than between two auditory channels or two visual channels. That
is, cross-modal time-sharing is better than intramodal. Wickens, Sandry, and Vidulich
(1983) found advantages to cross-modal over intramodal displays in both a laboratory
tracking experiment and a fairly complex flight simulation. Parkes and Coleman (1990)
found that discrete route guidance was better presented auditorily than visually while
subjects were concurrently driving a simulated vehicle (visual input). Wickens (1980)
reviews several other studies that report similar advantages.

However, the relative advantage of cross-modal (auditory-visual or AV) over in-
tramodal (VV and AA) time-sharing may not really be the result of separate perceptual
resources within the brain but rather the result of the peripheral factors that place the
two intramodal conditions at a disadvantage, as we discussed above. Thus, two com-
peting visual channels, if they are far enough apart, will require visual scanning between
them—an added cost, discussed in Chapter 3. If too close together, they may impose
confusion and masking, just as two auditory messages may mask one another. The de-
gree to which peripheral rather than central factors are responsible for the examples of
better cross-modal time-sharing remains uncertain, and when visual scanning is carefully
controlled, cross-modal displays do not always produce better time-sharing (Wickens &
Liu, 1988). However, in most real-world settings, visual scanning is enough of a factor that
dual-task interference can be reduced by off-loading some information channels from
the visual to the auditory modality. Simultaneous auditory messages are difficult enough to process that an advantage can usually be gained by displaying one of them visually (Rollins & Hendricks, 1980).

**Focal-Ambient Vision** In addition to the distinction between auditory and visual modalities of processing, there is good evidence that two aspects of visual processing, referred to as focal and ambient vision, appear to define separate resources in the sense of (a) supporting efficient time-sharing, (b) being characterized by qualitatively different brain structures, and (c) being associated with qualitatively different types of information processing (Leibowitz & Post, 1982; Weinstein & Wickens, 1992). Focal vision, which is nearly always foveal, is required for fine detail and pattern recognition. In contrast, ambient vision heavily (but not exclusively) involves peripheral vision and is used for sensing orientation and ego motion (see Chapter 4). When we successfully walk down a corridor while reading a book, we are effectively exploiting the parallel processing capabilities of focal and ambient vision, just as we are when keeping the car moving forward in the center of the lane (ambient vision) while reading a road sign (focal vision). The former heavily uses peripheral vision. Aircraft designers have considered several ways of exploiting ambient vision to provide guidance and alerting information to pilots while their focal vision is heavily loaded by perceiving specific channels of displayed instrument information (Stokes, Wickens, & Kite, 1990).

Although the focal-ambient distinction is not explicitly represented as a separate dimension within the multiple resource model in Figure 11.5, it may conveniently be represented within the processing codes dimension, which we discuss next.

**Processing Codes** The role that the spatial and verbal codes play in defining separate processing resources has been discussed in some detail in previous sections and chapters: ambient (exclusively spatial) and focal (often verbal or symbolic) vision in the previous section, spatial and verbal perceptual processes in Chapters 4, 5, and 6, the degree of interference within and between spatial and verbal working memory in Chapter 7, and the compatibility of these two codes with information display in Chapter 9. Data from multiple-task studies indicate that spatial and verbal processes, or codes, whether functioning in perception, working memory, or response, depend on separate resources and that this separation can often be associated with the two cerebral hemispheres (Polson & Friedman, 1988).

The separation of spatial and verbal resources seemingly accounts for the high degree of efficiency with which manual and vocal outputs can be time-shared, assuming that manual responses are usually spatial in nature and vocal ones are verbal. In this regard, investigations by Martin (1989); McLeod (1977); Tsang and Wickens (1988); Vidulich (1988); Wickens (1980); Wickens and Liu (1988); and Wickens, Sandry, and Vidulich (1983) have shown that tracking and a discrete verbal task are time-shared more efficiently when the latter employs vocal as opposed to manual response mechanisms. Discrete manual responses using the nontracking hand appear to interrupt the continuous flow of the tracking response, whereas discrete vocal responses leave this flow untouched (Wickens & Liu, 1988).

Finally, consider the near perfect time-sharing efficiency with which auditory shadowing (see Chapter 3) and visual-manual transcription tasks (typing from text and
sight-reading piano music, see Chapter 6) can be carried out by skilled operators, as demonstrated by Shaffer (1975) and by Allport, Antonis, and Reynolds (1972), respectively. This success is clearly due in large part to the separation of codes and modalities of processing of the two tasks. If the auditory shadowing and piano sight-reading task pair investigated by Allport, Antonis, and Reynolds is examined within the framework of Figure 11.5, we see that auditory shadowing is clearly auditory, verbal, and vocal. Piano sight-reading is visual and manual. If the further assumption is made that music involves right-hemispheric processing (Nebes, 1977), the two tasks may be considered to require predominately separate resources.

An important practical implication of the processing codes distinction is the ability to predict when it might or might not be advantageous to employ voice versus manual control. As noted by Brooks (1968) and confirmed in a more applied context by Wickens and Liu (1988), manual control may disrupt performance in a task environment imposing heavy demands on spatial working memory (e.g., driving), whereas voice control may disrupt performance of tasks with heavy verbal demands (or be disrupted by those tasks, depending on resource allocation policy). Thus, for example, the model predicts the potential dangers of manual dialing of cellular phones, given the visual, spatial, and manual demands of vehicle driving, and it suggests the considerable benefits to be gained from voice dialing (Goodman, Tijerna, Bents, & Wierwille, 1999).

When considering different resource modalities, it is important to recall that verbal tasks may be most compatibly responded to with voice control, and spatial tasks with manual control, as discussed in Chapter 9. Occasionally, then, the choice between control types may be dictated by a consideration of trade-offs between compatibility and resource competition, addressed explicitly by Wickens, Vidulich, and Sandry-Garza (1984; Wickens, Sandry, & Vidulich, 1983). Research generally indicates, however, that resource conflict, rather than compatibility, is the more dominant of the two forces in dual-task situations (Goettl & Wickens, 1989).

**Application** In applying the multiple resource model to understanding multiple-task interference, there are a few key points to keep in mind. First, the model predicts that the amount of interference will depend on the number of shared levels on all three dimensions. Thus, the mold does not imply that two tasks using separate levels on any one dimension (e.g., an auditory and visual task) will foster perfect time-sharing. Indeed, in this case both the auditory and visual task must involve some perceptual processing, which will be a source of resource competition, and therefore potential interference, unless one or both tasks are automated.

Second, the model is complimentary to, rather than competitive with, the single-resource demand mechanism described earlier in the chapter, and indeed, many task-interference situations can be easily understood by assuming a single-resource model (Liao & Moray, 1993). This is true whenever conditions or designs being compared do not differ in the qualitative makeup of their resource structure. Within a multiple-resource perspective, the degree of demand (task difficulty) within a resource will modulate the amount of competition with other tasks demanding the same resource, and this demand level could dominate the benefits of resource separation. Suppose, for example, we compare two different modality interfaces for displaying instructions to an automobile driver. The auditory display will create low perceptual interference with the
visual demands of driving; but if that display is coupled with a greater working-memory load, for example, to remember the implications of the instructions, this greater resource demand could overwhelm the benefits for the separate perceptual modalities. The precise mechanisms by which demand and resource differences are coupled to predict dual-task interference are beyond the scope of the current chapter but may be found in Navon and Gopher (1979) and Wickens (1991, 1992; Sarno & Wickens, 1995).

Confusion and Similarity

A hallmark of the mechanisms we have demonstrated so far is that they are associated with resource demand and strategic allocation, and with three relatively gross and anatomically defined dichotomies within the brain. Yet there appear to be several other sources of variance in time-sharing efficiency that cannot be described by the above mechanisms but, instead, are related to more continuous characteristics of the nature of the information processing activities, similar to the role of proximity discussed in Chapter 3. In this role, processing proximity is like a two-edged sword, having its benefits (to cooperation) as well as its costs (to confusion).

Cooperation The improvement of time-sharing efficiency by increasing similarity results from circumstances in which a common display property, mental set, processing routine, or timing mechanism can be cooperatively shared in the service of two tasks that are performed concurrently. We have noted in Chapter 3 how the close proximity fostered by a single object can improve parallel perceptual processing. Such object-based proximity, as well as other attributes of similarity between two display sources, has been found to improve performance of concurrent tracking tasks (Fracker & Wickens, 1989), such as the lateral and vertical dimensions of aircraft control (Haskell & Wickens, 1993). Levy, Foyle, and McCann (1998) found that the proximity of representation of tracking axes in three-dimensional space improved time-sharing between control of the flight axes.

With regard to central processing operations, there is some evidence that the performance of two tracking tasks is better if the dynamics on both axes are the same than if they are different, even if like dynamics are produced by combining two more difficult tasks (Chernikoff, Duey, & Taylor, 1960) (see Chapter 10). Even when the performance of two identical but difficult tasks is not actually better than the performance of a difficult-easy pair, performance of the difficult pair is less degraded than would be predicted by a pure resource model (Braune & Wickens, 1986; Fracker & Wickens, 1989). That is, there is an advantage for the identity of two difficult dynamics, which compensates for the cost of their difficulty.

A similar phenomenon has been observed in the domain of choice reaction time by Duncan (1979). He observed better time-sharing performance between two incompatibly mapped RT tasks than between a compatible and an incompatible one, in spite of the fact that the average difficulty of the incompatible pair was greater. Here again, the common rules of mapping helped performance. A series of investigations point to the superior time-sharing performance of two rhythmic activities when the rhythms are the same rather than different (Klapp, 1979, 1981; Peters, 1981), and investigators have noted that when a manual and vocal response are si-
multaneously mapped to a single stimulus (i.e., in a coordinated redundant fashion), then the bottleneck normally associated with simultaneous response selection is eliminated (Fagot & Pashler, 1992; Schvaneveldt, 1969).

These examples illustrate that similarity in information-processing routines leads to cooperation and facilitation of task performance, whereas differences lead to interference, confusion, and conflict, an issue we address in more detail shortly. Other aspects of identity and cooperation are also reflected in a kind of resonance or compatibility between similarity at one stage of processing and similarity at another. This resonance is described by the proximity compatibility principle (Wickens & Carswell, 1995), discussed in the context of object displays in Chapter 3, graphs in Chapter 4, and multitasking tracking in Chapter 10. Thus, for example, Fracker and Wickens (1989) and Chernikoff and Lemay (1963) found that two tracking tasks benefited from an integrated display if they shared similar dynamics, but not if the dynamics were different.

**Confusion** We have discussed ways in which increasing similarity of processing routines can bring about improved dual-task performance. A contradictory trend, in which the increasing similarity of processing material may reduce rather than increase time-sharing efficiency, is a result of confusion. For example, Hirst and Kalmar (1987) found that time-sharing between a spelling and mental arithmetic task is easier than time-sharing between two spelling or two mental arithmetic tasks. Hirst (1986) showed how distinctive acoustic features of two dichotic messages, by avoiding confusion, can improve the operator's ability to deal with each separately. Many of these confusion effects may be closely related to interference effects in memory, discussed in Chapter 7. Indeed, Venturino (1991) showed similar effects when tasks are performed successively, so that the memory trace of one interferes with the processing of the other.

Although these findings are similar in one sense to the concepts underlying multiple-resources theory (greater similarity producing greater interference), it is probably not appropriate to label these elements as "resources" in the same sense as the stages, codes, and modalities of Figure 11.5, since such items as a spelling routine or distinctive acoustic features hardly share the gross anatomically based dichotomous characteristics of the dimensions of the multiple-resources model (Wickens 1986, 1991). Instead, it appears that interference of this sort is more likely based on confusion, or a mechanism that Navon (1984; Navon & Miller, 1987) labeled outcome conflict. Responses (or processes) relevant for one task are activated by stimuli or cognitive activity for a different task, producing confusion or crosstalk between the two. The most notorious example of this phenomenon is in the Stroop task, discussed in Chapter 3, in which the semantic characteristics of a color word (white or blue) interfere with the subjects' ability to report the color of ink in which the word is printed. The necessary condition for confusion and crosstalk to occur is similarity. In the Stroop task, there is similarity both in the common location of the two stimulus properties and in their common reference to color. As a result, Stroop interference may be lessened either by reducing the physical similarity (increased distance) between the two attributes or by increasing the "semantic distance" between the color and semantic properties of the word (Klein, 1964). Thus, in manipulating physical distance, Stroop interference is reduced when the color word is placed next to a color patch rather than printed in the color ink (Kahneman & Chajczyk, 1983).
In semantic distance, color-related words like sky or grass produce some but reduced Stroop interference, whereas color-neutral words like but or office produce very little interference at all.

However, the Stroop task is a focused, not a divided-attention, task. Are confusion and crosstalk also mechanisms that cause dual-task interference? Experiments by Fracker and Wickens (1989) and by Navon and Miller (1987) suggest that they have at least some role. Navon and Miller studied subjects' abilities to categorize simultaneously words in two visually displayed word sequences. They found that items on one sequence that were similar to those on the other slowed down the response to the other, as if producing an outcome conflict. Fracker and Wickens asked subjects to perform two tracking tasks at the same time. By looking at the time-series analysis between input and output signals of the two tasks, they could measure the degree of crosstalk, in which the error of one task was compensated for by an unwanted control response of the hand controlling the other task. Generally this crosstalk was small, but when the displays and controls of the two axes were made more similar by integrating them, the crosstalk increased. However, this increase was not the source of increased tracking error, nor was there an increase in crosstalk when the resource demands of one of the tasks was increased, producing greater interference.

In summary, although confusion due to similarity certainly contributes to task interference in some circumstances, it is not always present or always an important source of task interference (Pashler, 1998; Fracker & Wickens, 1989). Its greatest impact probably occurs when an operator must deal with two verbal tasks requiring concurrently working memory for one and active processing (comprehension, rehearsal, or speech) for the other, or with two manual tasks with spatially incompatible motions. In the former case, as discussed in Chapter 7, similarity-based confusions in working memory probably play an important role.

**PRACTICAL IMPLICATIONS**

The practical implications of research and theory on attention and time-sharing are as numerous as the cases in which a human operator is called on to perform two activities concurrently, and his or her limitations in doing so represent a bottleneck in performance. These instances include the pilot of the high-performance aircraft who may have a variety of component tasks simultaneously imposed; the process control or nuclear power plant monitor who is trying to diagnose a fault and is simultaneously deciding, remembering, and scanning to acquire new information; the musical performer who is attending to notes, rhythm, accompanist, and the quality of his or her own performance; the learner of any skill who must concurrently perceive different stimuli associated with a task, make responses, and process feedback; or the vehicle driver who must drive safely while operating a navigational device or cellular phone. The safety implications of breakdowns in multiple-task performance are graphically revealed in the analysis of cellular phone use while driving by Violanti and Marshall (1996), who report accident rates five times those of driving without cellular phone use (see also Goodman, et al., 1999).

As with any domain of human performance, there are three broad categories of applications of attention theory: to system and task design, to operator training, and
to operator selection. The applications to the last two areas will be described only briefly. When operators must be trained for time-sharing in complex environments, such as the aircraft cockpit, as we noted earlier in this chapter, attention must be given both to the development of automaticity and to the training of time-sharing skills, issues that are discussed in considerable detail by Damos and Wickens (1980), Gopher (1991), Rogers, Rousseau and Fisk (1999), Schneider (1985), and Schneider and Detweiler (1988). Considerably more is known about training for automaticity than about the training of time-sharing skills (Gopher, 1991; Gopher, Weil, & Bareket, 1994). If operators are to be selected for task environments in which they will be required to engage in time-sharing activity, at issue is the extent to which tests can be derived that will predict success in time-sharing.

The third applications category, which will concern us most, is that of predicting multiple-task performance imposed by different task environments or system design features. This issue is also closely tied to the issues of predicting and measuring the mental workload imposed by these design features, to be discussed at the end of this chapter.

**Predicting Multiple-Task Performance**

Using the structural and demand characteristics of models like the multiple-resources model, system designers may be concerned with either relative or absolute predictions of task interference (Hart & Wickens, 1990). Relative predictions allow the designer to know ahead of time which of two or more configurations will provide better multiple-task performance. (This is closely related to the issue of which configuration will provide lower workload, a distinction to be made in the next section.) If the computer user wishes to move a cursor while reading a screen, will the two activities interfere least with keyboard, voice, or mouse control (Martin, 1989)? Should automated navigational commands be presented to the automobile driver auditorily or visually (Parkes & Coleman, 1990)? Should the in-vehicle cellular phone be “dialed” with voice or hands (Goodman, Tijerina, Bents, & Wierwille, 1999)?

To these sorts of questions, multiple-resource theory can provide some answers (Sarno & Wickens, 1995). For example, the adoption of voice recognition and synthesis technology (a talking, listening computer) may not provide many advantages—and may even be worse than a visual/manual interface—if the information exchange is to be carried out in an environment in which the operator must rehearse other verbal material. As we have seen before, voice technology will offer its greatest benefits for reducing task interference if the concurrent task demands are heavily spatial, as in computer-based design (Martin, 1989), or flying (Wickens, Sandry, & Vidulich, 1983).

The role of confusion in dual-task performance is also relevant to performance prediction. Where concurrent activity may be required, designers should not impose two different tasks using similar material. For example, the entering or transcription of digital data will be disrupted if others in the surrounding environment are currently speaking digits, but less so if others are engaged in normal conversations.

An interesting application here concerns the presence of music as background or entertainment for operators engaged in various tasks. Multiple-resource theory would predict relative independence between the perception of music (more associated with
spatial/analog processing) and the involvement with tasks that are manual or verbal. This prediction seems to be consistent with the results of a study by Tayyari and Smith (1987), who found no interference between "light orchestral" music listening (at up to 85 decibels) and visual-manual data entry (and in fact a slight improvement in the speed of data entry). Similarly, Martin, Wogalter, and Forlano (1988) found no interference between instrumental music and reading comprehension, but did find that comprehension suffered when lyrics were added, thus imposing a dual load on the verbal code.

Relative predictions may also be based on any quantifiable variables that are predicted to increase mental workload. Often these are "count" variables such as the number of aircraft "handed" by an air traffic controller at any one time, the arrival rate of customers to a store clerk, or the traffic density encountered by a driver on the highway. It is straightforward (but important) to say that higher levels along these "count" scales often produce lower time-sharing performance than lower levels (relative prediction). However, where possible, human factors practitioners would also like to be able to define absolute performance predictions along the scales defined by such variables. For example, at what level of traffic density is workload "excessive"? Of course, the lower ranges of such scales do not place operators in a region in which they must engage in multiple-task performance. However, maximum advisable levels often serve as warnings, in that exceeding such levels will impose time-sharing or divided attention requirements, which would be considered an "overload" condition.

The goal of absolute predictions of task interference and task performance calls to mind the kind of question asked by the Federal Aviation Administration before certifying new aircraft: Are the demands imposed on the pilot excessive? If excessive is to be defined relative to some absolute standard, such as "80 percent of maximal capacity," an absolute question is being asked. A common approach to absolute workload and performance prediction is time-line analysis, which will enable the system designer to "profile" the workload that operators encounter during a typical mission, such as landing an aircraft or starting up a power-generating plant (Kirwan & Ainsworth, 1992). In a simplified but readily usable version, it assumes that workload is proportional to the ratio of the time occupied performing tasks to total time available. If one is busy with some measurable task or tasks for 100 percent of a time interval, workload is 100 percent during that interval. Thus, the workload of a mission would be computed by drawing lines representing different activities, of length proportional to their duration. The total length of the lines would be summed and then divided by the total time (Parks & Boucek, 1989), as shown in Figure 11.6. In this way, the workload encountered by or predicted for different members of a team (e.g., pilot, copilot, and flight engineer) may be compared and tasks reallocated if there is a great imbalance. Furthermore, epochs of peak workload or work overload, in which load is calculated as greater than 100 percent, can be identified as potential bottlenecks.

The straightforward assumption of time as the key component for performance prediction appears adequate in many circumstances (Hendy, Liao, & Milgram, 1997), particularly with multiple visual tasks that cannot share access to foveal vision (Liao & Moray, 1993). However, when these conditions do not apply, the basic research in multiple-task performance suggests at least four directions in which the time-line analysis described in Figure 11.6 needs to be extended to accurately predict performance. First,
it is clear that operators may not necessarily choose to time-share two tasks (as dictated by a particular time line) if they have an opportunity to reschedule (i.e., postpone) one or the other. Hence, effective time-line analysis should be coupled with models of task selection based on the kind of logic presented in Chapter 3 and discussed earlier in this chapter. These kinds of advancement have been made in a number of predictive models reviewed by Wickens (1990). Second, any time-line analysis must incorporate activities that are covert, such as planning or rehearsal. Covert actions are a much greater challenge to include than overt actions because their time duration cannot be as easily estimated, nor can they be easily "seen" by an analyst observing an operator performing a task. Yet it is clear that intense cognitive activity does compete with other perceptual and cognitive tasks, in a way that should be predicted. Ask any driver who has been distracted from careful driving by thinking about serious problems. Thus, such an extension requires the adoption of specialized techniques for cognitive task analysis (Seamster, Redding, & Kaempf, 1997; Gordon & Gill, 1997).

Third, as discussed earlier, the analysis must be sensitive to the differences in resource demands of different tasks. Two time-shared tasks will not impose a 100 percent workload if they are easy and automated but may very well exceed that value if they are difficult (Parks & Boucek, 1989). However, because more difficult tasks generally occupy more space on the time line (and hence will predict greater interference), the requirement for demand coding appears to be somewhat less critical for predicting multiple-task performance (Sarno & Wickens, 1995). Finally, an accurate time-line analysis model should incorporate the multiple-resources concept, recognizing that two tasks overlapping on the time line could provide either very efficient performance or very disruptive performance, depending on their degree of resource conflict. This issue has been addressed in time-line models proposed by North and Riley (1989), Sarno and Wickens (1995), and Plott (1995).

**Figure 11.6** Time-line analysis. The percentage of workload at each point is computed as the average number of tasks per unit time within each time window.
Assessing Mental Workload

Within the last three decades, the applied community has demonstrated considerable interest in the concept of mental workload: How busy is the operator? How complex are the tasks? Can any additional tasks be handled above and beyond those that are already performed? Will the operator be able to respond to unexpected events? How does the operator feel about the difficulty of the tasks being performed? The substantial number of articles, books, and symposia in the field (O’Donnell & Eggemeier, 1986; Gopher & Donchin, 1986; Tsang & Wilson, 1997; Hancock & Meshkati, 1988; Leplat & Welford, 1978; Moray, 1979, 1988; Smith, 1979; Williges & Wierwille, 1979; Hendy, Liao, & Milgram, 1997) is testimony to the fact that system designers and company managers realize that workload is an important concern. Organizational decisions to downsize or eliminate a position of employment must be made on the basis of whether the capacity of the remaining workers is adequate to still perform the remaining tasks (i.e., workload is not excessive). This was an issue in the late 1970s when a landmark decision was made to reduce the crew size of medium-range jet aircraft by eliminating the flight engineer’s position (Lerner, 1983); the decision was the result of a presidential commission formed to address the question. The Federal Aviation Administration requires certification of aircraft in terms of workload measures, and the Air Force and Army also impose workload criteria on newly designed systems. All of these concerns lead to a very relevant question: What is mental workload and how is it measured?

Importance of Workload

Designers and operators realize that performance is not all that matters in the design of a good system. It is just as important to consider what demand a task imposes on the operator’s limited resources. As shown in Figure 11.1, demand may or may not correspond with performance. More specifically, the importance of research on mental workload may be viewed in three different contexts: workload prediction (discussed in the previous section in the context of multitask performance prediction), the assessment of workload imposed by equipment, and the assessment of workload experienced by the human operator. The difference between the second and third is their implications for action. When the workload of systems is assessed or compared, the purpose of such a comparison is to optimize the system. When the workload experienced by an operator is assessed, it is for the purpose of choosing between operators or providing an operator with further training. Workload in all three contexts may be initially represented by a simplified single-resource model of human processing resources. (We consider the added complexities of multiple-resource theory later.) The supply-demand function in Figure 11.7 shows the relationship between the important variables in this model. The resources demanded by a task are shown on the horizontal axis. The resources supplied are shown on the vertical axis, along with the level of performance. If adequate performance of a task demands more resources from the operator than are available, performance will break down, as shown to the right. If, however, the available supply exceeds the demand, as shown to the left, then the amount of the excess expresses the amount of reserve capacity.

We make the assumption in this chapter that the concept of workload is fundamentally defined by this relationship between resource supply and task demand. In the region to the left of the break point of Figure 11.7, which we might call the “underload” region, workload is inversely related to reserve capacity. In the region to the right, it is inversely related to the level of task performance, as discussed in the previous
Equipment Assessment Although workload and performance prediction before a system is designed is desirable, it is often essential to measure the workload of a system already existing at some stage of production. This assessment may be made to identify those bottlenecks in system or mission performance in which resource demands momentarily exceed supply and performance breaks down. Alternatively, workload may be assessed to compare two alternate pieces of equipment that may achieve similar performance but differ in their resource demands because they possess differently shaped performance resource functions (see, e.g., Figure 11.1). Sometimes the criterion of workload may offer the only satisfactory means of choosing between alternatives. As we have noted, an even greater challenge to workload assessment techniques is posed by the requirement to determine if the absolute level of workload imposed by a system is above or below a given absolute criterion level. The goal of developing workload certification criteria for complex systems has spawned the need for such absolute scales.

Assessing Operator Differences Workload measures may also assess differences in the residual resources available to reflect changes and differences in operator capacity, rather than system demand. This may be done in one of two contexts: (1) The level of skill or automaticity achieved by different operators who may be equivalent in their primary-task performance may be compared. For example, Crosby and Parkinson (1979) and Damos (1978) showed that flight instructors differed from student pilots in their level of residual attention. Damos furthermore found that applied to students, this measure was a good predictor of subsequent success in pilot training. (2) Operators may be
monitored on-line in real task performance. In this case, intelligent computer-based systems could decide to assume responsibility for the performance of certain tasks from the human operator when momentary demands were measured to exceed capacity (Scerbo, 1996; Wickens & Gopher, 1977), although this form of on-line human-computer interaction, known as adaptive automation, requires a certain level of cooperation from the human operator (see Chapter 13).

Criteria for Workload Indexes O'Donnell and Eggemeier (1986) propose a number of criteria that should ideally be met by any technique to assess workload. Of course it is true that some of these criteria may trade off with one another, and so rarely if ever will one technique be found that satisfies all criteria. The following list of five criteria of a workload index is similar to the list proposed by O'Donnell and Eggemeier.

Sensitivity. The index should be sensitive to changes in task difficulty or resource demand.

Diagnosticity. An index should indicate not only when workload varies but also the cause of such variation. In multiple-resource theory, it should indicate which of the capacities or resources are varied by demand changes in the system. This information makes it possible to implement better solutions.

Selectivity. The index should be selectively sensitive only to differences in resource demand and not to changes in such factors as physical load or emotional stress, which may be unrelated to mental workload or information-processing ability.

Obtrusiveness. The index should not interfere with, contaminate, or disrupt performance of the primary task whose workload is being assessed. This is particularly true if workload is being assessed while operators are performing real (nonlaboratory) tasks, especially in safety critical environments (e.g., vehicle driving).

Bandwidth and Reliability. As with any measure of behavior, a workload index should be reliable. However, if workload is assessed in a time-varying environment (e.g., if it is necessary to track workload changes over the course of a mission), it is important that the index offer a reliable estimate of workload rapidly enough so that the transient changes may be estimated (Humphrey & Kramer, 1994).

A myriad of workload assessment techniques have been proposed, some meeting many of these criteria, but few satisfying all of them. These may be classified into four broad categories related to primary-task measures, secondary-task measures of spare capacity, physiological measures, and subjective rating techniques.

Primary-Task Measures In evaluating any system or operator, one should always examine first the performance on the system of interest, like computer data-entry speed, driving deviations from the center of the lane, or learning comprehension with a particular method of instruction. Because this is the target of evaluation, we refer to the task performed with this system as the primary task. Yet there are four important reasons that primary-task performance may be insufficient to reveal clearly the merits of the primary task. First, in Figure 11.7, two primary tasks may lie in the “underload” region of the supply-demand space (see the two tasks represented by the PRPs in Figure 11.1). Since both have
sufficient reserve capacity to reach perfect performance, the latter measure cannot discriminate between them. Second, two primary tasks to be compared may differ in how they are measured or what those measures mean. A designer of prosthetic devices to enable the blind to read may find that the two kinds of devices produce qualitatively different forms of errors (e.g., semantic confusions versus letter confusions) or that they differ greatly in the speed-accuracy trade-off. As we saw in Chapter 10, comparisons of systems at different levels of speed and accuracy are possible but much less certain than if either accuracy or speed comparisons are identical.

Third, sometimes it is simply impossible to obtain good measures of primary-task performance. As noted in Chapter 8, decision making may impose tremendous cognitive demands on the operator, yet the performance outcome (right or wrong) is a very poor measure of all of the mental operations that were involved in reaching the final outcome. As discussed in Chapter 2, vigilance tasks may impose very high levels of workload (Hancock & Warm, 1989), but by their very nature, the performance data of vigilance can be very sparse.

Finally, two primary tasks may differ in their performance, not by the resources demanded to achieve that performance, but by differences in data limits. In decision making, for example, if a heuristic yields lower performance than a computational algorithm, this may be important information for the system or job designer, but this difference does not mean that the heuristic imposes greater workload. In fact, as suggested by the two PRFs in Figure 11.3, the difference may well be the result of the lower resource demands of the heuristic. Similarly, automated voice-recognition systems often yield poorer performance than manual data-entry systems for simple data strings. Yet this difference may be attributable to machine limits in the voice-recognition algorithm rather than to operator difference in the speed and resource demands of response production. In short, primary-task performances may differ for a lot of reasons that are not related to workload, as the latter is defined in the context of Figure 11.7.

For these reasons, system designers have often turned to the three other workload assessment techniques—secondary-task performance, physiological measures, and subjective measures—which may assess more directly either the effort invested into primary-task performance or the level of residual capacity available during that performance.

**The Secondary-Task Technique**  Imposing a secondary task as a measure of residual resources or capacity not utilized in the primary task (Cgden, Levine, & Eisner, 1979; Rolfe, 1973) is a technique that has a long history in the field of workload research. Secondary-task performance is assumed to be inversely proportional to the primary-task resource demands. In this way, secondary tasks may reflect differences in task resource demand, automaticity, or practice that are not reflected in primary-task performance. The logic behind the secondary task in the PRF space is shown in Figure 11.8. The operator is requested to perform as well as possible on the primary task and then allocate any left over resources to the secondary task. Thus, as we see in Figure 11.8a, three increasing levels of primary task difficulty will yield three successively smaller margins of available resources, and therefore three diminishing levels of secondary-task performance. As just one example, Bahrick and Shelly (1958) found that the secondary task was sensitive to differences in automaticity. Performance of their subjects on a serial RT task (the primary task) did not differ between a random and a predictable sequence of
stimuli. However, performance on a secondary task did discriminate between them. With practice, the repeated sequence required fewer resources.

As we have noted, when using the secondary-task technique, the investigator is interested in variation in the secondary-task decrement (from a single secondary-task control condition) to infer differences in primary-task demand. The primary task is thus both the task of interest and the task whose priority is emphasized, as shown in Figure 11.8a. In contrast, a variant of the secondary-task technique is the use of a loading task (Ogden, Levine, & Eisner, 1979; Rolfe, 1973), shown in Figure 11.8b, in which different allocation instructions are provided. The subject is now asked to devote all necessary resources to the loading task, and the degree of intrusion of this task on performance of the primary task is examined to compare differences between primary tasks.

**Secondary Task Examples** A multitude of secondary tasks have been proposed and employed at one time or another to assess the residual capacity of primary tasks. Although the reader is referred to reviews by Ogden, Levine, and Eisner (1979), O'Donnell and Eggemeier (1986), and Tsang and Wilson (1997) for a more exhaustive listing of these tasks, a few prominent candidates are described here.

In the rhythmic tapping task, the operator must produce finger or foot taps at a constant rate (Michon, 1966; Michon & Van Doorne, 1967). Tapping variability increases as primary-task workload increases. Random number generation requires the operator to generate a series of random numbers (Baddeley, 1966; Logic et al., 1989; Wetherell, 1981). As workload increases, the degree of randomness declines and the operator begins to generate more repetitive sequences (e.g., 456, 456, 456). Probe reaction time tasks...
are commonly used as workload measurement techniques, as it is assumed that greater primary-task workload will prolong the reaction time to a secondary-task stimulus (Kantowitz, Bortolussi, & Hart, 1987; Lansman & Hunt, 1982; Wetherell, 1981). Such tasks may involve lesser or greater degrees of processing complexity. For example, the Sternberg memory-search RT task described in Chapter 9 can provide a diagnosis of the primary tasks that impose greater load on working memory (Crosby & Parkinson, 1979; Wetherell, 1981; Wickens et al., 1986).

Time production and time estimation are two related techniques with somewhat different underlying assumptions (Zakay, Block, & Tsal, 1999). If the operator is asked to produce time intervals of a constant duration (e.g., 10 seconds), the intervals will tend to be overestimated when there are higher demands (Hart, 1975), as if the higher levels of workload interfere with (and postpone) whatever internal mechanism is responsible for mental time counting. (As suggested by the tapping task of Michon, 1966, high workload will also make these intervals more variable.) In contrast, if the operator is asked to estimate (retrospectively) durations of time that have passed (“how long has it been since you started the task”), two somewhat different and opposing phenomena appear to operate. On the one hand, to the extent that we estimate the average passage of time by a certain amount of work accomplished, then high workload can lead to overestimation (“to accomplish all I have done, I must have been working more than 10 minutes”). On the other hand, there are circumstances when time “drags,” when we are bored (very low workload), and this too will increase estimates (“I’ve been waiting for hours”). These two contradictory trends suggest that retrospective estimates may be increased at both lower and higher workload levels, but may also offset each other, rendering retrospective technique a less than fully reliable technique, in contrast to time production (Hart, 1975).

Benefits and Costs of Secondary Tasks The secondary-task technique has two very distinct benefits. First, it has a high degree of face validity. It is designed to predict the amount of residual attention an operator will have available if an unexpected failure or environmental event occurs. This validity places the technique in contrast with the physiological and subjective measures described below. Second, the same secondary task can be applied to two very different primary tasks and will give workload measures in the same units (which can therefore be compared). As we have seen, this is not the case with primary-task performance measures.

One difficulty is that the secondary-task technique must account for the fact that there are different kinds of resources (O’Donnell & Eggemeier, 1986). Workload differences that result from changes in a primary-task variable can be greatly underestimated if the resource demands of the primary-task variation do not match those of most importance for secondary-task performance. Thus, the secondary-task index is not always sensitive. For example, the secondary task of vocally responding to heard digits (auditory verbal speech) would mismatch the resource demands of driving (a visual-spatial manual task) and, hence, might underestimate driving workload.

Kahneman (1973) proposes that the ideal secondary-task technique is one that employs a battery of secondary-task measures sensitive to different resources in the system. Schlegel, Gilliland, and Schlegel (1986) propose a structured set of tasks, known as the criterion task set, that are mapped onto different resource dimensions. When it is clear that one level of a dimension does not contribute to primary-task performance,
the dimensionality of the battery may be reduced accordingly. For example, a verbal processing task with no spatial components need not be assessed by a spatial secondary task. However, in cases in which an activity is performed that potentially engages all "cells" of processing resources, as depicted in Figure 11.5, a secure secondary task workload estimate should involve a battery that also incorporates those cells, or at least taps early and late processing of a verbal and spatial nature.

A second problem often encountered with the secondary-task technique is that it may interfere with and disrupt performance of the primary task; that is, the technique suffers on the obtrusiveness criterion (Wierwille, Rahimi, & Casali, 1985). On the one hand, this may be inconvenient or even dangerous if the primary task is one like flying or driving; a diversion of resources to the secondary task at the wrong time could lead to an accident. On the other hand, disruption of the primary task could present problems of interpretation if the amount of disruption suffered by two primary tasks to be compared is not the same. That is, the measurement technique differentially disrupts that which is being measured.

Problems with obtrusiveness often affect the operator's attitude toward and willingness to perform the secondary task. In response, some researchers have advocated embedded secondary tasks. Here the "secondary task" is actually a legitimate component of the operator's total task responsibilities, but it is a component of lower priority in the task hierarchy than the primary task of interest (Raby & Wickens, 1994). For example, the latency of responding to a verbal request from air traffic control would be a good embedded task for assessing the pilot's workload demands of keeping the aircraft stable, since the latter is of higher priority. In driving, one might consider the frequency of glances to the rearview mirror as an embedded secondary task to assess the workload of vehicle control.

Physiological Measures One solution to performance obtrusiveness is to record, unobtrusively, the manifestations of workload or increased resource mobilization through appropriately chosen physiological measures of autonomic or central nervous system activity (Kramer, 1987). Three such techniques are briefly described here, and a further review is provided by O'Donnell and Eggemeier (1986), and Tsang and Wilson (1997).

Heart-Rate Variability A number of investigators have examined different measures associated with the variability or regularity of heart rate as a measure of mental load. Variability is generally found to decrease as the load increases, particularly that variability which cycles with a period of around 10 seconds (0.1 Hz) (Mulder & Mulder, 1981). When this variability is associated specifically with the periodicities resulting from respiration, the measure is termed sinus arrhythmia (Mulder & Mulder, 1981; Tattersal & Hockey, 1995; Sirevaag et al., 1993; Vicente, Thornton, & Moray, 1987). Heart-rate variability is sensitive to a number of different difficulty manipulations and therefore appears to be more sensitive than diagnostic. Derrick (1988) investigated this measure with four quite different tasks performed in different combinations within the framework of the multiple-resource model. His data suggest that the variability measure reflected the total demand imposed on all resources within the processing system more than the amount of resource competition (and therefore dual-task decrement) between tasks.

Pupil Diameter Several investigators have observed that the diameter of the pupil correlates quite closely with the resource demands of a large number of diverse cognitive
activities (Beatty, 1982) These include mental arithmetic (Kahneman, Beatty, & Pollack, 1967), short-term memory load (Beatty & Kahneman, 1966; Peavler, 1974), air traffic control monitoring load (Jorna, 1997), and logical problem solving (Bradshaw, 1968, see Beatty, 1982, for an integrative summary). This diversity of responsiveness suggests that the pupiometric measure may be highly sensitive, although as a result it is undiagnostic. It will reflect demands imposed anywhere within the system. Its disadvantage, of course, is that relevant pupil changes are in the order of tenths of a millimeter, which means that accurate measurement requires considerable head constraint and precise measuring equipment. Additionally, changes in ambient illumination must be monitored, since these also affect the pupil. Because of its association with the autonomic nervous system, the measure will also be susceptible to variations in emotional arousal.

**Visual Scanning** While discussed as a measure of attention allocation in Chapter 3, visual scanning—the direction of pupil gaze—can also contribute extensively to workload modeling in two different ways. First, as we have noted, dwell time can serve as an index of the resources required for information extraction from a single source. In an aircraft simulation, Bellenkes, Wickens, and Kramer (1997) found that dwells were largest on the most information-rich flight instrument (the attitude directional indicator or ADI; see Chapter 3), and that dwells were much longer for novice than expert pilots, reflecting the novice's greater workload in extracting the information. Second, scanning can be a diagnostic index of the source of workload within a multi-element display environment. For example, Bellenkes, et al. found that long novice dwells on the ADI were coupled with more frequent visits and, hence, served as a major "sink" for visual attention. Little time was left for novices to monitor other instruments, and as a consequence, their performance declined on tasks using those other instruments. Dinges, Orne, Whitehouse, and Orne (1987) and Wikman, Nieminen, and Summala (1998) used scanning as a critical measure of the in-vehicle head-down time caused by the workload associated with different in-vehicle systems such as maps, radio buttons, etc. Thus, scanning measures can contribute to modeling the strategic aspects of resource allocation, as discussed earlier in this chapter.

**Costs and Benefits** Physiological indexes have two great advantages: (1) They provide a relatively continuous record of data over time. (2) They are not obtrusive into primary-task performance. On the other hand, they often require that electrodes be attached (heart measures) or some degree of physical constraints be imposed (pupiometric measures, eye fixations), and therefore they are not really unobtrusive in a physical sense. These constraints will influence user acceptance. Many physiological measures have a further potential cost in that they are, generally, one conceptual step removed from the inference that the system designers would like to make. That is, workload differences measured by physiological means must be used to infer that performance breakdowns would result or to infer how the operator would feel about the task. Secondary- or primary-task measures assess the former directly, whereas subjective measures, which we now discuss, assess the latter.

**Subjective Measures** A variety of techniques have been proposed to assess the subjective effort required to perform a task. Some of them use a structured rating scale to elicit a single dimensional rating (Wierwille & Casali, 1983), whereas others have
adopted the view that subjective workload, like the resource concept itself, has several dimensions (Derrick, 1988; O'Donnell & Eggemeier, 1986). Two common multidimensional assessment techniques are the NASA Task Load Index (TLX) scale (Hart & Staveland, 1988), which assesses workload on each of five 7-point scales, and the subjective workload assessment (SWAT) technique (Reid & Nygren, 1988), which measures workload on three 3-point scales (see Table 11.1). Each of these techniques has formal prescriptions for how the multiple scales may be combined to obtain a single measure. Although both scales tend to yield similar outcomes when they are applied to the same set of data (Vidulich & Tsang, 1986), the TLX technique, having a greater number of scales and greater resolution per scale, allows it to convey more information, and appears to provide a more reliable measure (Hill et al., 1992).

Costs and Benefits The benefits of subjective techniques are apparent. They do not disrupt primary-task performance, and they are relatively easy to derive. Their costs relate to the uncertainty with which an operator's verbal statement diagnostically reflects the investment or demand for processing resources and is not influenced by other biases (e.g., dislike or unfamiliarity of the task, or rater's reluctance to report that things are difficult).

### TABLE 11.1 Two Multi-Dimensional Workload Rating Scales

<table>
<thead>
<tr>
<th>SWAT Scale</th>
<th>Mental Effort Load</th>
<th>Stress Load</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time Load</strong></td>
<td><strong>Mental Effort Load</strong></td>
<td><strong>Stress Load</strong></td>
</tr>
<tr>
<td>1. Often have spare time. Interruptions or overlap among activities occur infrequently or not at all.</td>
<td>1. Very little conscious mental effort or concentration required. Activity is almost automatic, requiring little or no attention.</td>
<td>1. Little confusion, risk, frustration, or anxiety exists and can be easily accommodated.</td>
</tr>
<tr>
<td>2. Occasionally have spare time. Interruptions or overlap among activities occur frequently.</td>
<td>2. Moderate conscious mental effort or concentration required. Complexity of activity is moderately high due to uncertainty, unpredictability, or unfamiliarity. Considerable attention required.</td>
<td>2. Moderate stress due to confusion, frustration, or anxiety noticeably adds to the workload. Significant compensation is required to maintain adequate performance.</td>
</tr>
<tr>
<td>3. Almost never have spare time. Interruptions or overlap among activities are very frequent, or occur all the time.</td>
<td>3. Extensive mental effort and concentration necessary. Very complex activity requiring total attention.</td>
<td>3. High to very intense stress due to confusion, frustration or anxiety. High to extreme determination and self-control required.</td>
</tr>
</tbody>
</table>

(continues)
TABLE 11.1 (continued)

<table>
<thead>
<tr>
<th>Title</th>
<th>Endpoints</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>MENTAL DEMAND</td>
<td>Low/High</td>
<td>How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?</td>
</tr>
<tr>
<td>PHYSICAL DEMAND</td>
<td>Low/High</td>
<td>How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?</td>
</tr>
<tr>
<td>TEMPORAL DEMAND</td>
<td>Low/High</td>
<td>How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?</td>
</tr>
<tr>
<td>PERFORMANCE</td>
<td>Perfect/Failure</td>
<td>How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?</td>
</tr>
<tr>
<td>EFFORT</td>
<td>Low/High</td>
<td>How hard did you have to work (mentally and physically) to accomplish your level of performance?</td>
</tr>
<tr>
<td>FRUSTRATION LEVEL</td>
<td>Low/High</td>
<td>How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during your task?</td>
</tr>
</tbody>
</table>

Relationship Between Workload Measures

If all measures of workload demonstrated high correlation with one another and the residual disagreement was due to random error, there would be little need for further validation research in the area. The practitioner could adopt whichever technique was methodologically simplest and most reliable for the workload measurement problem at hand. Generally, high correlations between measures will be found if the measures
are assessed across tasks of similar structure and widely varying degrees of difficulty. For example, Jex and Clement's (1979) found a high correlation between subjective and secondary task measures of flight-control difficulty (e.g., tracking order as discussed in Chapter 10). However, the correlations may not be high and may even be negative when quite different tasks are contrasted. For example, consider an experiment conducted by Herron (1980) in which an innovation designed to assist in a target-aiming task was subjectively preferred by users over the original prototype but generated reliably poorer performance than the original. Similar dissociations have been observed by Childress, Hart, and Bortalussi (1982) and Murphy et al. (1978), who measured pilot workload associated with cockpit-display innovations.

We use the term dissociation to describe these circumstances in which conditions that are compared have different effects on different workload measures. The understanding of attention and resource theory can be quite useful in interpreting why these dissociations occur. Yeh and Wickens (1988) paid particular attention to the dissociation between primary task and subjective measures. Their assumption is that subjective measures directly reflect two factors: the effort that must be invested into performance of a task and the number of tasks that must be performed concurrently. These two factors, however, do not always influence performance in the same way. To illustrate, consider the following situations:

1. If two different tasks are in the underload region on the left of Figure 11.7, the greater resources invested on the more difficult task (and therefore the higher subjective workload) will not yield better performance.

2. If the operator performs the three tasks shown in Figure 11.8b while investing full resources, performance will differ, but the resources invested (and therefore the subjective workload experienced) will not differ. Subjective measures often fail to reflect differences due to data limits, particularly if the lower level of performance caused by the lower level of the data limit is not immediately evident to the performer who is giving the rating. (Note in Table 11.1, however, that this is an advantage of NASA TLX measure, which allows the operator to separately rate "performance" and "mental effort").

3. If two systems are compared, one of which induces a greater investment of effort, the latter will probably show higher subjective workload, even as its performance is improved (through the added effort investment). This dissociation is shown when effort investment is induced through monetary incentives (Vidulich & Wickens, 1986). However, it also appears that greater effort is invested when better (e.g., higher resolution) display information is available to achieve better performance. Thus, in tracking tasks, features like an amplified error signal (achieved through magnification or prediction—see Chapter 10) will increase tracking performance but at the expense of higher subjective ratings of workload (Yeh & Wickens, 1988).

4. Yeh and Wickens (1988) have concluded that a very strong influence on subjective workload is exerted by the number of tasks that must be performed at once. The subjective workload from time-sharing two (or more) tasks is almost always greater than that from a single task. We can see here the source of another dissociation with performance because a single task might be quite difficult (and result in poor performance as a result), whereas a dual-task combination, if the
tasks are not difficult and use separate resources, may indeed produce a very good performance in spite of its higher level of subjective load.

The presence of dissociations often leaves the system designer in a quandary. Which system should be chosen when performance and workload measures do not agree on the relative merits between them? The previous discussion, and the chapter as a whole, do not provide a firm answer to this question. However, the explanation for the causes of dissociation and its basis on a theory of resources should at least help the designer to understand why the dissociation occurs, and thus why one measure or the other may offer a less reliable indicator of the true workload of the system in specific circumstances.

### Consequences of Workload

Increases on workload do not inherently have “bad” consequences. In many environments, it is the low levels of workload that, when coupled with boredom, fatigue, or sleep loss, can have negative implications for human performance (Chapter 2; Huey & Wickens, 1993). Given some flexibility, operators usually work homeostatically to achieve an “optimal level” of workload by seeking tasks when workload is low, and shedding them when workload is excessive (Hart & Wickens, 1990). This basis for strategic task management was discussed earlier in the chapter.

In revisiting these task management issues, we must highlight the importance of understanding the strategy of task management that operators adopt when workload becomes excessive (i.e., crosses from the underload to the overload region of Figure 11.7 as measured by the techniques described above). At a most general level, four types of adaptation are possible. (1) People may allow performance of tasks to *degrade*, as a vehicle driver might allow lane position to wander as the workload of dealing with an in-vehicle automation system increases. (2) People may perform the tasks in a more efficient, less resource-consuming way. For example, in decision making, they may shift from optimal algorithms to satisfactory heuristics. (3) People may shed tasks altogether, in an “optimal” fashion, eliminating performance of those of lower priority. For example, under high workload, the air traffic controller may cease to offer pilots weather information unless requested, while turning full attention to traffic separation. (4) People may shed tasks in a nonoptimal fashion, abandoning those that should be performed. As an example here, we end the chapter as we began both the chapter and the book, with the unfortunate driver who chose to shed that most critical task of roadway monitoring to address the high workload of failure diagnosis. Unfortunately, beyond the material covered earlier in this chapter on resource allocation, very little is known about general principles that can account for when people adopt one strategy or the other. Perhaps the one principle that can be stated with most certainty is that training and expertise play a strong role in successful workload management (Orasanu & Fischer, 1997), and so it is no surprise that such training has been a formalized component of many training programs in high-risk multi-task environments like aviation (Wiener, Kanki, & Helmreich, 1993).

### Transition

In this chapter we have outlined the potential causes of multiple-task interference, discussing the role of switching, confusion, and cooperation but emphasizing most heavily
the role of resource competition. The consideration of resources led to the discussion of the theory and measurement of mental workload and the fundamental importance of the resource concept to this theory.

Stress is often a consequence of high levels of mental workload, particularly if such workload is sustained for some time. Stress in turn will often produce changes in functioning of all of the information processing components that we have discussed, and so will produce effects on performance. Of course, stress may be experienced from other sources than high workload—sleep loss, noise, and anxiety, to name a few. In the following chapter, we will examine some of these sources of stress and determine whether and how their effects might be predicted.

A second consequence of high workload is the occurrence of errors. However, as with stress, errors may be caused by other factors as well. In the following chapter, we will see that one of the prominent effects of stress is a shift in the speed-accuracy trade-off to error-prone performance. Furthermore, errors may be caused by the characteristics of the task and by differences in the skill level of the operator. Thus, in the next chapter we will describe the causes and models of human error and show how human factors engineers have tried to use this information to predict human reliability and to design error-tolerant systems. Because of the close linkage between stress and errors and because both may be related to all stages of processing, they are included together in a single chapter.

REFERENCES


Chapter 11 Attention, Time-Sharing and Workload


