CHAPTER 5

INFORMATION PROCESSING

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1 INTRODUCTION

Information processing lies at the heart of human performance. In a plethora of situations in which humans interact with systems, the operator must perceive information, transform that information into different forms, take actions on the basis of the perceived and transformed information, and process the feedback from that action, assessing its effect on the environment. These characteristics apply whether information processing is defined in terms of the classic open-loop information-processing model that derives from much of psychological research (Figure 1*a*) or the closed-loop model of Figure 1*b*, which has its roots within both control engineering (e.g., Pew and Baron, 1978; McRuer, 1980; Jagacinski and Flach, 2003) and more recent conceptualizing in ecological psychology (Flach et al., 1995; Hancock et al., 1995). In either case, *transformations* must be made on the information as it flows through the human operator. These transformations take time

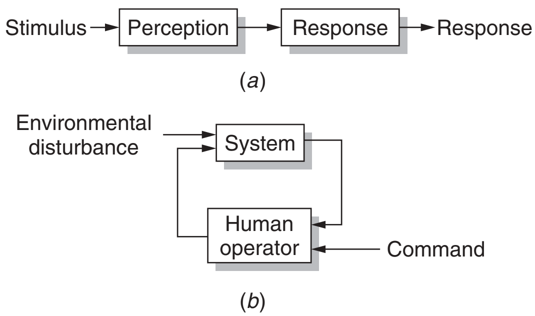

Figure 1 Two representations of information processing: (*a*) traditional open-loop representation from cognitive psychology; (*b*) closed-loop system, following the tradition of engineering feedback models.

and may be the source of error. Understanding their nature, their time demands, and the kinds of errors that result from their operation is critical to predicting and modeling human–system interaction.

In this chapter we describe characteristics of the different important *stages* of information processing, from perception of the environment to acting on that environment. We try to do so in a way that is neither too specific to any particular system nor so generic that the relevance of the information-processing model to system design is not evident. We begin by contrasting three ways in which information processing has been treated in applied psychology, and then we describe processes and transformations related to *attention, perception, memory* and *cognition, action selection*, and *multiple-task performance*.

2 THREE APPROACHES TO INFORMATION PROCESSING

The classic information-processing approach to describing human performance owes much to the seminal work of Broadbent (1958, 1972), Neisser (1967), Sternberg (1969), Posner (1978), and others in the decades of the 1950s, 1960s, and 1970s, who applied the metaphor of the digital computer to human behavior. In particular, as characterized by the representation in Figure 1*a*, information was conceived as passing through a finite number of discrete stages. These stages were identifiable, not only by experimental manipulations, but also by converging evidence from brain physiology. For example, it makes sense to distinguish a perceptual stage from one involving the selection and execution of action, because of the morphological distinctions between perceptual and motor cortex.

There is also a human factors rationale for the stage distinction made by information-processing psychology. This is because different task or environmental factors appear to influence processing differentially at the different stages, a distinction that has certain design implications. For example, the *aging process* appears to affect the selection and execution of actions more than the speed of perceptual encoding (Strayer et al., 1987). Immersed displays may improve perceptual–motor interaction, even as they inhibit the allocation of attention (Olmos et al., 2000), and different sources of workload may have different influences on the different stages (Wickens and Hollands 2000). Decision-making biases can be characterized by whether they influence perception, diagnosis, or action selection (Wallsten, 1980; Wickens and Hollands, 2000), and the different stages may also be responsible for the commission of qualitatively different kinds of errors (Reason, 1990; see Chapter 27). The support that automation provides to the human operator can also be well represented within the information-processing stage taxonomy (Parasuraman et al., 2000, 2008). Within the stage approach, there is no need to assume that processing starts at stage 1. For example, if one has an intention to act, processing can start with the response.

In contrast to the stage approach, the *ecological approach* to describing human performance provides much greater emphasis on the integrated flow of information through the human rather than on the distinct, analyzable stage sequence (Gibson, 1979; Flach et al., 1995; Hancock et al., 1995). The ecological approach also emphasizes the human's integrated interaction with the *environment* to a greater extent than does the stage approach, which can sometimes characterize information processing in a more context-free manner. Accordingly, the ecological approach focuses very heavily on modeling the perceptual characteristics of the environment to which the user is "tuned" and responds in order to meet the goals of a particular task. Action and perception are closely linked, since to act is to change what is perceived, and to perceive is to change the basis of action in a manner consistent with the closed-loop representation shown in Figure 1*b*.

As a consequence of these properties, the ecological approach is most directly relevant to describing human behavior in interaction with the natural environment (e.g., walking or driving through natural spaces or manipulating objects directly). However, as a direct outgrowth, this approach is also quite relevant to the design of controls and displays that mimic characteristics of the natural environment—the concept of *direct-manipulation interfaces* (Hutchins et al., 1985). As a further outgrowth, the ecological approach is relevant to the design of interfaces that mimic characteristics of how users *think* about a physical process, even if the process itself is not visible in a way that can be represented directly. In this regard, the ecological approach has been used as a basis for designing effective displays of energy conversion processes such as those found in a nuclear reactor (Vicente and Rasmussen, 1992; Moray et al., 1994; Vicente et al., 1995; Burns, 2000; Vicente, 2002; Burns et al., 2004).

Because of its emphasis on interaction with the natural (and thereby familiar) environment, the ecological approach is closely related to other approaches to performance modeling that emphasize people working with domains and systems about which they are experts. This feature characterizes, for example, the study of *naturalistic decision making* (Zsambock and Klein, 1997;

Kahneman and Klein, 2009; see Chapter 3), which is often set up in contrast to the representation of decision making within an information-processing framework (Wickens and Hollands, 2000).

Both the stage-based approach and the ecological approach have a great deal to offer to human factors, and the position we take in this chapter is that aspects of each can and should be selected, as they are more appropriate for analysis of the operator in a particular system. For example, the ecological approach is highly appropriate for modeling vehicle control, but less so for describing processes in reading, understanding complex instructions under stress, or dealing with highly symbolic logical systems (e.g., the logic of computers, information retrieval systems, or decision tree analysis; see Chapter 8). Finally, both approaches can be fused harmoniously, as when, for example, the important constraints of the natural environment are analyzed carefully to understand the information available for perception and the control actions allowable for action execution in driving, but the more context-free limits of information processing can be used to understand how performance might break down from a high load that is imposed on memory or dual-task performance requirements in a car.

A final approach, that of *cognitive engineering*, or *cognitive ergonomics* (Rasmussen et al., 1995; Vicente, 1999, 2002; Bizants and Roth, 2007; Jenkins et al., 2009), is somewhat of a hybrid of the two described above. The emphasis of cognitive engineering is, on the one hand, based on a very careful understanding of the environment and task constraints within which an operator works, a characteristic of the ecological approach. On the other hand, as suggested by the prominence of the word *cognitive*, the approach places great emphasis on modeling and understanding the knowledge structures that expert operators have of the domains in which they must work and, indeed, the knowledge structures of computer agents in the system. Thus, whereas the ecological approach tends to be more specifically applied to human interaction with physical systems and environments (particularly those that obey the constraints of Newtonian physics), cognitive engineering is relevant to the design of almost any system about which the human operator can acquire knowledge, including the very symbolic computer systems, which have no physical analogy.

Whether human performance is approached from an information-processing, ecological, or cognitive engineering point of view, we assert here that, in almost any task, a certain number of mental processes involved in selecting, interpreting, retaining, or responding to information may be implemented, and it is understanding the vulnerabilities of these processes and capitalizing, where possible, on their strengths which can provide an important key to effective human factors of system design.

In this chapter we adopt as a framework the information-processing model depicted in Figure 2 (Wickens and Hollands, 2000). Here stimuli or events are *sensed and attended* (Section 3) and that information received by our sensory system is *perceived*, that is, provided with some meaningful interpretation based on memory of past experience (Section 4). That which is perceived may be responded to directly, through a process of action selection (decision of what act to take) and execution (Section 6). Alternatively, it may be stored temporarily in working memory, a system that may also be involved in thinking about or transforming information that was not sensed and perceived but was generated internally (e.g., mental images, rules, Section 5). Working memory is of limited capacity and heavily demanding of attention in its operation but is closely related to our large-capacity long-term memory, a system that stores vast amounts of information about the world, including both facts and procedures, and

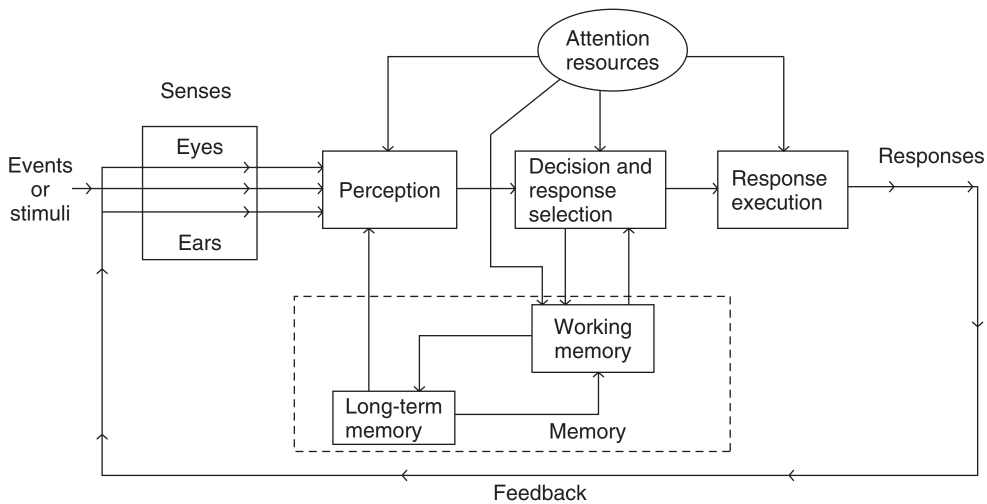

Figure 2 Model of human information processing. (Adapted from Wickens, 1992.)

retains that information without attention but not always fully available for retrieval.

As noted in the figure and highlighted in the ecological approach, actions generally produce feedback which is then sensed to complete the closed-loop cycle. In addition, human attention, a limited resource, plays two critical roles in the information-processing sequence (Wickens, 2007; Wickens and McCarley, 2008). As a selective agent, it chooses and constrains this information that will be perceived (Section 3). As a task management agent, it constrains what tasks (or mental operations) can be performed concurrently (Section 7).

3 SELECTING INFORMATION

Since Broadbent's (1958) classic book, it has been both conventional and important to model human information processing as, in part, a filtering process. This filtering is assumed to be carried out by the mechanisms of *human attention* (Kahneman, 1973; Parasuraman et al., 1984; Damos, 1991; Pashler, 1998; Johnson and Proctor, 2004). Attention, in turn, may be conceptualized as having three *modes*: Selective attention chooses what to process in the environment, focused attention characterizes the efforts to sustain processing of those elements while avoiding distraction from others, and *divided attention* characterizes the ability to process more than one attribute or element of the environment at a given time.

We discuss below the human factors implications of the selective and focused attention modes and their relevance to visual search and discuss those of divided attention in more detail in Sections 4.6 and 7.

3.1 Selective Attention

In complex environments, selective attention may be described in terms of how it is influenced by the combined force of four factors: salience, effort, expectancy, and value (Wickens et al., 2003). These influences can often be revealed by eye movements when visual selective attention is assessed by visual scanning; obviously, however, eye movements cannot reflect the selectivity between vision and the other sensory modalities, such as auditory or tactile (Sarter, 2007).

1. *Salient features* of the environment will attract, or "capture," attention. Thus, auditory sounds tend to be more attention grabbing than visual events, leading to the choice of sounds to be used in alarms (Stanton, 1994; see also Chapterx 24). Within a visual display, the onset of a stimulus (e.g., increase in brightness from zero, or the appearance of an object where one was not present previously) tends to be the most salient or attention-attracting property (Yantis, 1993; Egeth and Yantis, 1997); other features, such as uniqueness, can also attract attention, but these are typically less powerful than onsets. The prominent role of onsets as attention-capturing devices can explain the value of repeated onsets ("flashing") as a visual alert. Salient events are sometimes described as those that govern *bottom-up* or stimulus-driven allocation of attention, to be contrasted with knowledge-driven or *top-down* features of selective attention, which we describe next in the context of expectations.
2. *Expectancy* refers to knowledge regarding the probable time and location of information availability. For example, frequently changing areas are scanned more often than slowly changing areas (Senders, 1980). Thus, drivers will keep their eyes on the road more continuously when the car is traveling fast on a curvy road than when traveling slowly on a straight one. The former has a higher "bandwidth." Also, expectancy defines the role of cueing in guiding attention. For example, an auditory warning may direct attention toward the display indicator that the warning is monitoring, because the operator will now expect to see an abnormal reading on that display.
3. *Value* is a third factor. High-frequency changes are not, however, sufficient to direct attention. The driver will not look out the side window despite the fact that there is a lot of perceptual "action" there, because information in the side window is generally not relevant to highway safety. It has already passed. Thus, selective attention is also driven by the *value* of information received at different locations. This describes the importance of knowing that information in carrying out useful tasks, or the costs of failing to note important information. It is valuable for the driver to look forward, because of the cost of failing to see a roadway hazard or of changing direction toward the side of the road. Thus, the effect of expectancy (bandwidth or frequency) on the allocation of selective attention is modulated by the value, as if the probability of attending somewhere, $p(A)$, is equal to the *expected value* of information sources to be seen at that location (Moray, 1986; Wickens et al., 2003; Wickens et al., 2008). Indeed, Moray (1986) and Wickens et al. (2003) find that well-trained, highly skilled operators scan the environment very much as if their attention is driven primarily and nearly exclusively by the multiplicative function of expectancy and value. Thus, we may think of the well-trained operator as developing scanning *habits* that internalize the expectancy and value of sources in the environment, defining an appropriately calibrated *mental model* (Bellenkes et al., 1997).
4. The final factor that may sometimes influence attention allocation is a negative one, and this factor, unique to eye movements, is the *effort* required to move attention around the environment. Small attention movements, such as scanning from one word to the next in a line of text or a quick glance at the speedometer in a car, require little effort. However, larger movements, such as shifting the eyes *and* head to check the side-view mirrors in a car, or coupling these

with rotation of the trunk to check the "blind spot" before changing lanes, requires considerably more information access effort (Ballard et al, 1995; Wickens, 1993). Indeed, the role of the information access effort also generalizes to the effort costs of using the fingers to manipulate a keyboard and access printed material that might otherwise be accessed by a simple scan to a dedicated display (Gray and Fu, 2001). The effort to shift attention to more remote locations may have a minimal effect on the well-rested operator with a well-trained mental model who knows precisely the expectancy and value of information sources (Wickens et al., 2003). However, the combination of fatigue (depleting effort) and a less well calibrated mental model can seriously inhibit accessing information at effortful locations, even when such information may be particularly valuable.

Collectively, the forces of salience, effort, expectancy, and value on attention can be represented by a visual attention model called SEEV, in which $P(\mathrm{A}) = S - \mathrm{EF} + \mathrm{EX} \times V$ (Wickens et al., 2003, 2008, 2009a; Horrey et al., 2006). Good design should try to reduce these four components to two by making valuable information sources salient (correlating salience and value) and by minimizing the effort required to access valuable *and* frequently used (expected) sources. For example, head-up displays (HUDs) in aircraft and automobiles are designed to minimize the information access effort of selecting the view outside and the information contained in important instruments (Fadden et al., 2001; Wickens et al., 2004). Reduced information access effort can also be achieved through effective layout of display instruments (Wickens et al., 1997).

While SEEV may predict what **is** attended, and salience highlights the roll of bottom-up attention capture, a large body of research has also recently focused on *attentional blindness,* particularly *change blindness,* highlighting the events in the world that are not noticed, even when they may be valuable (Simons and Levin, 1997 Rensink, 2002; Wickens et al., 2009a).

It seems that the human's attention system is not well designed to notice unexpected events, particularly when they appear in peripheral vision, under conditions of high workload. Naturally if these events are not salient as well (e.g., the offset of a stimulus, or a change in a word, say from "off" to "on"), then noticing will degrade still further. While in many circumstances such events may be noticed a majority of the time, when the events are safety critical (as in the above, "on" designating the activation of power) and relatively rare (referred to as "black swans"; Taleb, 2007; Wickens et al., 2009a), human miss rates as low as 10–20% can illuminate the safety concerns of change blindness (Wickens, 2009).

3.2 Focused Attention

While selective attention dictates where attention should travel, the goal of focused attention is to maintain processing of the desired source and avoid the distracting influence of potentially competing sources. The primary sources of breakdowns in focused attention are certain physical properties of the visual environment (clutter) or the auditory environment (noise), which will nearly guarantee some processing of those environments, whether or not such processing is desired. Thus, any visual information source within about 1° of visual angle of a desired attentional focus will disrupt processing of the latter to some extent (Broadbent, 1982). Any sound within a certain range of frequency and intensity of an attended sound will have a similar disruptive effect on auditory focused attention (Banbury et al., 2001; see Chapter 3). However, even beyond these minimum limits of visual space and auditory frequency, information sources can be disruptive of focused attention if they are salient.

3.3 Discrimination and Confusability

A key to design that can address issues of both selective and focused attention is concern for *discrimination* between information sources. Making sources discriminable by space, color, intensity, frequency, or other physical differences has two benefits. First, it will allow the display viewer to *parse* the world into its meaningful components on the basis of these physical features, thereby allowing selective attention to operate more efficiently (Treisman, 1986; Yeh and Wickens, 2001; Wickens et al., 2004). For example, an air traffic controller who views on her display all of the aircraft within a given altitude range depicted in the same color can easily select all of those aircraft for attention to ascertain which ones might be on conflicting flight paths. Parsing via a discrimination will be effective as long as all elements that are rendered physically similar (and therefore are parsed together) share in common some characteristic that is relevant for the user's *task* (as in the example above, all aircraft at the same altitude represent potential conflicts).

Second, when elements are made more discriminable by some physical feature, it is considerably easier for the operator to *focus* attention on one and ignore distraction from another, even if the two are close together in space (or are similar in other characteristics). Here, again, in our air traffic control example, it will be easier for the controller to focus attention on the converging tracks of two commonly colored aircraft if other aircraft are colored differently than if all are depicted in the same hue.

Naturally, the converse of difference-based discriminability is similarity- (or identity-) based confusion between information sources, a property that has many negative implications for design. For example, industrial designers may strive for consistency or uniformity in the style of a particular product interface by making all touchpad controls the same shape or size. Such stylistic uniformity, however, may result in higher rates of errors from users activating the wrong control because it looks so similar to the control intended.

3.4 Visual Search

Discrimination joins with selective and focused attention when the operator is engaged in *visual search*, looking for something in a cluttered environment (Wickens and

McCarley, 2008). The task may characterize looking for a sign by the roadway (Holohan et al., 1978), conflicting aircraft in an air traffic control display (Remington et al., 2000), a weapon in an X-rayed luggage image (McCarley et al., 2004), a feature on a map (Yeh and Wickens, 2001), or an item on a computer menu (Fisher et al., 1989). *Visual search models* are designed to predict the time required to find a target. Such time predictions can be very important for both safety (e.g., if the eyes need to be diverted from vehicle control while searching) and productivity (e.g., if jobs require repeated searches, as in quality control inspection or menu use).

The simplest model of visual search, based on a *serial self-terminating search* (Neisser et al., 1964), assumes that a *search space* is filled with items most of which are *nontargets* or *distracters*. The mean time to find a target is modeled to be $\mathrm{RT} = NT/2$, where N is the number of items in the space, T is the time to examine each item and determine that it is *not* a target before moving on to the next, and division by 2 reflects the fact that on average the target will be reached after half of the space is searched, but sometimes earlier and sometimes later. Hence, the variance in search time will also grow with N. Importantly, in many displays, we can think of N as a very functional measure of *clutter* (Yeh and Wickens, 2001).

The elegant and simple prediction of the serial self-terminating search model often provides a reasonable accounting for data (Yeh and Wickens 2001; Remington et al., 2000) but is also thwarted (but search performance is improved) by three factors that characterize search in many real-world search tasks: bottom-up parallel processing, top-down processing, and target familiarity. The first two can be accommodated by the concept of a *guided search model* (Wolfe, 2007; Wolfe and Horowitz, 2004). Regarding parallel processing, as noted in Section 3.1, certain features (e.g., uniqueness, flashing) will capture attention because they can be preattentively processed or processed in parallel (rather than in series) with all other elements in the search field. Hence, if the target is known to contain such features, it will be found rapidly, and search time will be unaffected by the number of nontarget items in the search field. This is because all nontarget items can be discriminated automatically (as discussed in Section 1) and thereby eliminated from imposing any search costs (Yeh and Wickens, 2001; L. D. Wickens, Alexander et al., 2004). For example, in a police car dispatcher display, all cars currently available for dispatching can be highlighted, and the dispatcher's search for the vehicle closest to a trouble spot can proceed more rapidly. Stated in other terms, search is "guided" to the subset of items containing the single feature which indicates that they are relevant. If there is more than a single such item, the search may be serial between those items that remain. *Highlighting* (Fisher et al., 1989; L. D. Wickens, Alexander et al., 2004; Remington et al., 2000) is a technique that capitalizes on this guided search.

Regarding top-down processing, search may also be guided by the operator's knowledge of *where* the target is most likely to be found. Location expectancy, acquired with practice and expertise, will create search strategies that scan the most likely locations first, to the extent that such predictability exists in the searched environments. For example, tumors may be more likely to appear in some parts of an organ than others, and skilled radiologists capitalize on this in examining an X ray in a way that novices do not (Kundel and Nodine, 1978). However, such a strategy may not be available to help the scanner of luggage X rays for weapons, because such weapons may be hidden anywhere in the luggage rather than in a predicable location (McCarley et al., 2004).

A second influence of top-down processing on search is the expectancy of whether a target will be present or not, the "target prevalence rate." Wolfe et al. (2005) observe that a low expectancy for targets will lead searchers to terminate their search prematurely, even though the target may still be present in the cluttered search field.

A third factor that can speed visual search, target familiarity is, like guided search, related to experience and learning and, like parallel search, related to salient features. Here we find that repeated exposures to the same consistent target can speed the search for that target and, in particular, reduce the likelihood that the target may be looked at (fixated) but not actually detected (McCarley et al., 2004). With sufficient repetition looking for the same target (or target possessing the same set of features), the expert tunes his or her sensitivity to discriminate target from nontarget features, and with extensive practice, the target may actually "pop out" of the nontargets, as if its discriminating features are processed preattentively (Schneider and Shiffrin, 1977). Further, even if a target does not become sufficiently salient to pop out when viewed in the visual periphery, repeated exposure can help ensure that it will be detected and recognized once the operator has fixated on it (McCarley et al., 2004).

The information processing involved in visual search culminates in a target detection decision, which sometimes may be every bit as important as the search operations that preceded it. In the following section we examine this detection process in its own right.

4 PERCEPTION AND DATA INTERPRETATION

4.1 Detection as Decision Making

At the top of many display design checklists is a reminder that critical targets must be detectable in the environment for which they are intended (e.g., Travis, 1991; Sanders and McCormick, 1993). Assuring such detectability might seem to be a simple matter of knowing enough about the limits of the operator's sensory systems to choose appropriate levels of physical stimulation, for example, appropriate wavelengths of light, frequencies of sound, or concentrations of odorants. Human sensitivity to the presence and variation of different physical dimensions is reviewed in Chapter 3, and these data must be considered limiting factors in the design of displays. Yet the detectability of any critical signal is also a function of the operator's goals, knowledge, and expectations. As noted in our discussion of

Table 1 Joint Contingent Events Used in Signal Detection Theory Analysis

Operator's Decision (Response Criterion)	State of the World: Signal	State of the World: No Signal (Noise)
Signal	Hit	False alarm
No signal	Miss	Correct rejection

visual search, there are plenty of opportunities for targets that are clearly above threshold to be missed when the operator is hurried and the display is cluttered. As we noted in our discussion of change blindness above, the magnitude of the superthreshold changes in a scene that can be missed is often surprising (Rensink, 2002).

The interpretive and vulnerable nature of even the simplest signal detection task becomes most apparent when we consider that missing a target is not the only possible detection error; we may also make *false alarms*, responding as if a signal is present when it is not (see Table 1). *Signal detection theory* (SDT) provides a valuable conceptual and computational framework for describing the processes that can lead to both types of errors (Green and Swets, 1989; Wickens, 2002; MacMillan and Creelman, 2005). In SDT, signals are never assumed to occur against a "clean" background of zero stimulation. Instead, all signals occur against a background of fluctuating *noise.* The noise arises from both internal (e.g., baseline neuronal activity) and external sources. The observer's detection task is thus, in reality, a *decision* task: Is the level of stimulation experienced at any moment the results of high levels of noise or does it represent the presence of a signal? Because noise is always present and is always fluctuating in intensity, detection errors are inevitable.

To deal with the uncertainty inherent in detection, SDT asserts that operators choose a level of sensory excitation to serve as a *response criterion*. If excitation exceeds this criterion, they will respond as if a signal is present. Operators who raise their response criteria, making them more conservative, will also increase the likelihood of missing targets. Lowering their criteria, however, will decrease the number of misses at the expense of increased false alarms. Signal detection theory provides a way to describe the criterion set by a particular operator performing a particular detection task and of determining the optimality of the selected criterion in the face of task characteristics such as signal probabilities and the relative repercussions (i.e., practical outcomes) of making the two types of errors.

Signal detection theory formally demonstrates that as signal probability increases, response criteria should be lowered in order to minimize overall error rates. People performing laboratory detection tasks tend to adjust their response criteria in the direction prescribed by SDT; however, they do *not* tend to adjust them far enough (Green and Swets, 1989). Probability-related shifts in response criteria also seem to occur in a wide variety of operational settings. For example, Lusted (1976) found that physicians' criteria for detecting particular medical conditions were influenced by the base rate of the abnormality (probability of signal). Similarly, industrial inspectors adjusted their criteria for fault detection based on estimated defect rates (Drury and Addison, 1973), although they fail to adjust their criteria enough when defect rates fall below 5% (Harris and Chaney, 1969). Many errors in the judicial process may also be linked to the biasing effects of implicit and potentially unreliable clues about signal probability. Saks et al. (2003) argue that such probability estimates influence the performance of forensic scientists asked to detect critical matches in evidence such as fingerprints, bite marks, and bomb residues. Research has also demonstrated an effective intervention for operators with overly low response criteria: Inserting "false signals" into some inspection tasks can increase perceived signal probability and, as a result, shift response criteria downward (Baker, 1961; Wilkinson, 1964).

A second factor that should influence the setting of the response criterion, according to SDT, is the relative costs associated with misses and false alarms and the relative benefits of correct responses. As an extreme example, if there were dire consequences associated with a miss and absolutely no costs for false alarms, the operator should adopt the lowest criterion possible and simply respond as if the signal is there at *every* opportunity. Usually, however, circumstances are not so simple. For example, a missed (or delayed) air space conflict by the air traffic controller or a missed tumor by the radiologist may have enormous costs, possibly in terms of human lives. However, actions taken because of false alarms, such as evasive flight maneuvers or unnecessary surgery, also have costs. The operator should adjust his or her response criterion downward to the degree that misses are more costly than false alarms and upward to the extent that avoiding false alarms is more important.

An important use of SDT in human factors research is often to diagnose the source of unsatisfactory detection performance. Has the operator failed to appropriately calibrate his or her response criterion to actual signal probabilities and response outcomes? Or, are limitations in the sensitivity of the operator's own (internal) signal-processing systems at fault? Depending on the answers to these questions, interventions can be devised to enhance detection performance. In the case of sensory limitations, engineering innovations may be required to enhance the fundamental signal-to-noise ratio, or greater target exposure may be necessary to enhance the operator's sensory tuning to critical target features (Gold et al., 1999). For example, attempts to increase the performance of airport luggage screeners have led to the development of a threat image projection (TIP) system for on-the-job training (Schwaninger and Wales, 2009). The system intermittently projects "false threat" images onto actual X-ray images, giving screeners greater exposure to potential targets (increasing overall sensitivity) and increasing their estimates of signal probability as well (thus, keeping their response criteria relatively low).

The job of the baggage screener exemplifies a combination of demands that can prove particularly challenging to operators—detection of low-probability signals over lengthy monitoring periods. Such *vigilance tasks*, and the predictable *vigilance decrements* in detection performance that occur as the watch progresses, have been the target of extensive research over much of the last century (Warm, 1984). In reviewing this literature, Warm et al. (2008) have argued that vigilance tasks are a part of many modern jobs and are both more mentally demanding and stressful than is often realized. As a way of dealing with such demands and the relatively poor detection performance that often results, designers often develop alarms and alerts to assist or sometimes replace the operator (Stanton, 1994). Yet considerable evidence suggests that such automation does not eliminate the detection problem. Automated alerts must also confront challenging issues of distinguishing signals from highly similar noise (e.g., friend and foe on a military image display), and such alert systems can be counted on to create errors. Thus, the alarm designer, rather than the human monitor, is now the agent responsible for adjusting the response criterion of the alarm, to trade off misses versus false alarms, and designers are often tempted to make this adjustment in such a way that signals are never missed by their systems. (Consider the possible litigation if a fire alarm fails to go off.) However, when the human and automation are considered as a total system, the resulting increase in automation false alarms can have serious consequences (Sorkin and Woods, 1985; Dixon et al., 2007). These consequences arise because a high false-alarm rate can lead to serious issues of *automation mistrust*, in which people may ignore the alarms altogether (Sorkin, 1989) and experience the “cry wolf” phenomenon (Breznitz, 1983).

The analysis of diagnostic systems also reveals that the problems of high false-alarm rates will be further amplified to the extent that the signals to be detected themselves occur rarely—the “low-base-rate problem,” as is often the case with alarm systems (Parasuraman et al., 1997), so that a large majority of the alarms that do sound will be false alarms. Answers to these problems lie in part in making available to human perception the raw data of the signal domain that is the basis of the alarm (Wickens et al, 2009b); and this appears to mitigate or even eliminate the cry-wolf effect. There is some evidence that *likelihood alarms* that can signal their own degrees of certainty in graded form (rather than a two-state on–off logic) will assist (Sorkin and Woods, 1985; St. Johns and Manes, 2002). Finally, it is reasonable to assume that training operators as to the nature of the mandatory miss/false-alarm trade-off, and the inevitable high false-alarm rate when there are low-base-rate events, should mitigate problems of distrust to some degree.

4.2 Expectancy, Context, and Identification

We have seen that our knowledge and expectations about the world help determine the efficiency of both our visual search and signal detection performance. Based on our past experience, attention can be directed to locations where targets are more likely to occur and response criteria can be adjusted according to the perceived likelihood or value of signals. We now consider how our ability to identify enormous numbers of objects from a variety of vantage points, often under less than optimal conditions, is also dependent on prior knowledge. Much research in object perception has been devoted to determining how the co-occurrence of particular stimulus attributes helps define individual objects (e.g., Biederman, 1987). However, research in cognitive psychology and computer vision has also provided compelling demonstrations of how our knowledge of statistical dependencies across entire scenes and events helps us make “educated guesses” about the likely identity of constituent objects (Oliva and Torralba, 2010).

Many studies, ranging from those using simple, artificial stimuli to those using complex, naturalistic scenes, have demonstrated that objects and attributes are recognized more quickly when they are embedded in consistent contexts (i.e., those in which the targets are naturally and frequently found) rather than when presented alone or in inconsistent contexts. Words are more efficiently identified when embedded in meaningful sentences rather than alone (e.g., Tulving et al., 1964). Individual letters are recognized more efficiently when embedded in words rather than when presented alone or as part of nonwords (Reicher, 1969). Caricature facial features require less physical detail for recognition when they are embedded in a face (Palmer, 1975). Photographs of naturalistic scenes also seem to enhance the identification of objects typically found there (Biederman et al., 1981). Even relatively subtle (but meaningful) object relations can influence identification; for example, an image of a glass is identified more rapidly when presented with an image of a pitcher that has its spout oriented toward the glass rather than away from it (Green and Hummel, 2006).

Explanations for context effects generally assume that added items in the stimulus array will increase the odds that the operator will recognize at least some portion of it. Even if the portion immediately recognized is not the target object, the recognition is still useful because it reduces the likelihood that some stimuli will be encountered while increasing the likelihood of others. In this way, the total set of possible objects, words, or letters from which the observer must choose becomes smaller and more manageable [see Massaro (1979) and McClelland and Rumelhart (1981) for formal models].

It is important to note that not all research on context effects focuses on our use of knowledge about contingencies among and within perceptual objects. Some researchers are more interested in identifying global *scene statistics* that might constrain the processing (and enhance the efficiency) of our interpretation of local scene elements (e.g., Ariely, 2001). These global properties may not be as subjectively accessible as the objects that form the scene, but they may provide an efficient means to reduce perceptual load. These statistics may include the mean size and variance of a set of objects, the center of mass, and textural properties (Oliva and Torralba, 2010). Evidence is accumulating that we do, in fact, extract global scene statistics such as mean object size, even of nonattended display elements (e.g., Chong and Treisman, 2005).

Taken together, these findings suggest that the old design maxim that "less is more" may well be wrong when the goal is to support the operator's identification of task-critical information. Unlike performance in visual search tasks, where additional nontarget stimuli or events usually cause declines in performance, identification tasks often benefit from the presence of additional stimuli, as long as those stimuli are normally encountered in spatial or temporal proximity to the target. In fact, operator expectancies can be used to offset degraded stimulus conditions such as poor print reproductions, faulty lighting, brief stimulus exposures, presentation to peripheral vision, or even the momentary diversion of attention. Therefore, the redundant use of red, an octagonal shape, and the letters S–T–O–P enhances the identification of a stop sign, as does its expected location to the driver's right immediately before an intersection. A "less is more" stop sign that only used the letter S as a distinguishing feature would not be advised!

In addition to the design implications of providing a *consistent* context for critical information, context effects also warn of the dangers of contextual *inconsistency*. The detection of such inconsistencies by safety professionals may be particularly useful for identifying environmental hazards. For example, a sidewalk interrupted by isolated steps may be a dangerous spot for a fall if not surrounded by changes in scene texture that typically indicate abrupt changes in landscape elevation [see Cohen (2003) for further examples of expectancy effects in trips and falls]. The availability of normative scene statistics may one day contribute to the identification of such hazards and is consistent with the ecological approach to human information processing.

4.3 Judgments of Two-Dimensional Position and Extent

Both detection and identification are categorical judgments. Sometimes, however, we may be more interested in determining specific qualitative properties of a stimulus such as its location and the magnitude of its various properties (e.g., length, volume, orientation). These judgments are critical for manual control and locomotion (see Section 6) as well as for the interpretation of maps, graphs, and dynamic analog indicators. In this section we focus mainly on spatial judgments of static formats before turning to their dynamic counterparts.

It is well known that the spatial judgments required to read even the most everyday graphs are prone to systematic distortions, knowledge of which can sometimes be used to manipulate a graph's message [e.g., Penrose (2008) evaluates the prevalence of such distortions in corporate annual reports]. Some examples include:

1. Our overestimation of values represented in bar graphs, especially with shorter bars and those farthest from the *y* axis (Graham, 1937)
2. The perceptual flattening of line graphs with respect to the *y* axis, resulting in larger underestimations of the represented data as the reader follows the line from its origin (Poulton, 1985)
3. Cyclic patterns of bias in estimations of part–whole relationships (e.g., reading pie charts) that are dependent on the number of available reference points on the graphs (Hollands and Dyre, 2000)
4. Distance distortions between cursor locations and target/icon locations induced by the shape of the cursor (overestimations and overshooting occur when the cursor is an arrow pointed toward the target; Phillips et al., 2003)

These distortions in distance and size may be special cases of geometric illusions such as those reviewed by Gillam (1980) and Gregory (1980). Poulton (1985), for example, has ascribed the perceptual flattening of lines in graphs to the Poggendorf illusion (Figure 3*a*). Phillips et al. (2003) refer to the Muller–Lyer illusion (Figure 3*b*) when describing the overestimations of distances between cursor and target. A variety of information-processing mechanisms have been proposed for such illusions, including misallocation of attention, and our tendency to misapply depth cues to wo-dimensional (2D) images. Whatever the cause, design modifications can reduce the impact of these illusions. Poulton (1985), for example, found that simply adding a redundant *y* axis to the right side of his graphs effectively reduced point-reading errors. Lowlighted horizontal gridlines can have the same beneficial effect. Kosslyn (2006) describes more ways to minimize the likelihood of these graphical illusions as well as ways to reduce graphical miscommunication more generally.

Although there are many salient examples of the use of perceptual illusions to misrepresent data in graphical displays, the presence of illusions is not always harmful. Some designers have even used illusions of size to increase traffic safety. Shinar et al. (1980) painted a pattern similar to that used to induce the Wundt illusion (see Figure 3*c*) on a roadway leading to a dangerous obscured curve. After the roadway was painted, drivers tended to reduce their speed before encountering the curve, presumably because the pattern made the road seem narrower.

The most systematic work on the size and nature of errors in the perception of graphical displays has focused

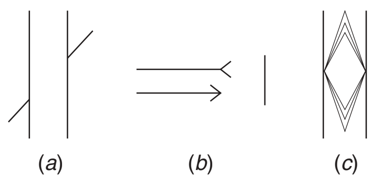

Figure 3 Three perceptual illusions, influencing the perception of location and spatial extent: (*a*) Poggendorf illusion, in which two diagonal line segments that are actually collinear do not appear so; (*b*) Muller–Lyer illusion, in which the distances between the horizontal line segment and the tips of the two arrowheads appear to be different, even though they are not; (*c*) Wundt illusion, in which two parallel vertical lines appear to curve inward.

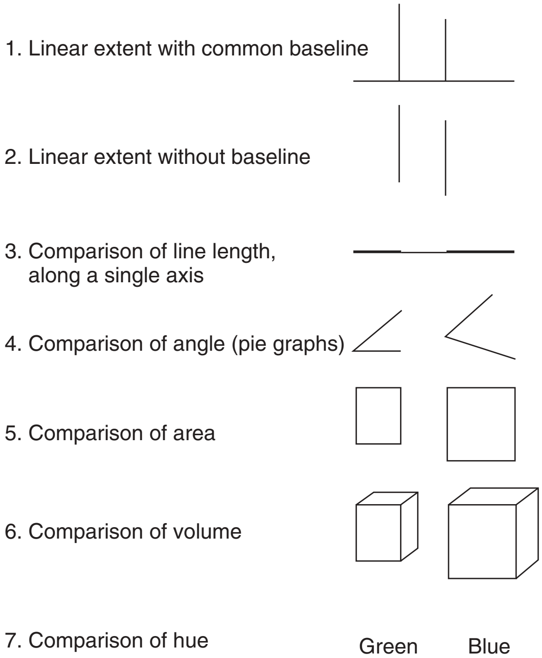

Figure 4 Graphical dimensions for making comparative judgments. (From Wickens, 1992; used by Cleveland and McGill, 1985.)

on how precisely we can make comparisons *between* data values. Cleveland and McGill (1984; Cleveland, 1985) developed a list of the physical dimensions that are commonly used to represent data in graphs and maps. These dimensions were ordered, as shown in Figure 4, in terms of the accuracy with which they could be used to make relative-magnitude judgments (e.g., "What percentage is point *A* of point *B*?"). Using this list as a guide, designers are advised, for example, to avoid using variation in volume or area to represent data. Thus, pictograms should usually be avoided in favor of bar charts or point displays. Similar lists have also been proposed for other sensory modalities. For example, Wall and Brewster (2003) have suggested that haptic graphs should use friction to represent data values rather than stiffness or the spatial period of sinusoidal textures.

Although a sensible first step in designing displays, lists of this type do not ensure the eventual efficacy of graphs. The Cleveland–McGill list of preferred graphical dimensions, for example, predicts performance in graph-reading tasks less well when users move from making simple comparisons to performing more integrative tasks such as describing trends (Carswell, 1992). Furthermore, each step down the Cleveland–McGill list is not equally detrimental to performance. Position, length, and angle judgments are associated with small differences from one another, but all three are used much more accurately than either area or volume. As we will see next, the misperception of volume and other spatial stimulus dimensions may reflect ambiguities in our perception of three-dimensional (3D) form and distance.

Additional comprehensive coverage of information-processing factors and biases in graph interpretation can be found in Kosslyn (2006), Gillan et al. (1998), and Wickens and Hollands (2000).

4.4 Judgments of Distance and Size in Three-Dimensional Space

Judgments of extent and position, discussed in the preceding section, are also made in 3D space, a space that can be either true space (e.g., judging whether there is adequate room to pass a car on a two-lane road) or a display-synthesized 3D space (e.g., comparing the volume of cubes in Figure 5). When making judgments in either real or synthesized virtual spaces, human perception depends on a host of cues to provide information about the absolute or relative distance from the viewer (Cutting and Vishton, 1995). Many of these depth cues are called *pictorial cues* because they can be used to generate the impression of depth in 2D pictures such as Figure 6. Here the convergence of the edges of the roadway at the horizon, the *linear perspective,* suggests that the roadway is receding. The decreasing grain of the texture of the cornfield moving

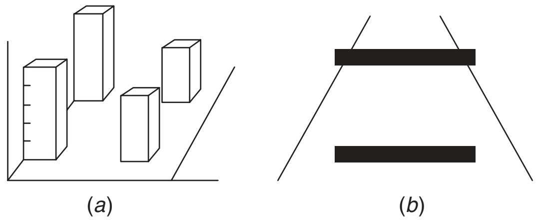

Figure 5 Role of size constancy in depth perception in creating illusions: (*a*) distorted overestimation of the size of the more distant bar graphs; (*b*) Ponzo illusion, illustrating the greater perceived length of the more distant bar.

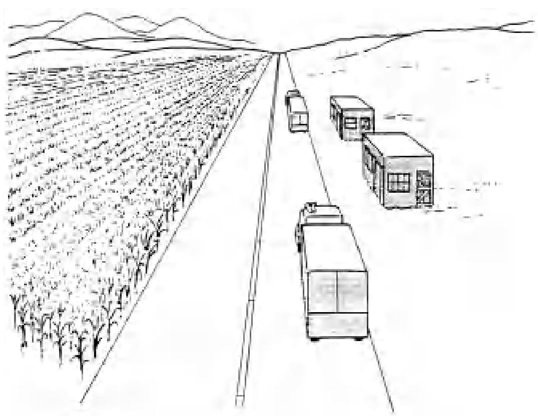

Figure 6 Perceptual cues for depth perception. (From Wickens, 1992.)

from the bottom to the top of the figure, the *textural gradient*, also informs us that the surface is receding, as well as revealing the slant angle of the surface and the vantage point of the viewer above the landscape. Three additional pictorial cues allow us to judge which building is closer. The building closer to the top of the image is signaled to be farther away (*height in the plane*), as is the building that captures the smaller retinal image (*relative size*); the building that obscures the contours of the other is seen to be closer (*interposition* or occlusion).

In addition to the pictorial cues, which are part of the image itself, there are five cues that result from characteristics of the viewer. *Motion parallax* results whenever the viewer moves, with nearer objects producing greater relative motion across the visual field than distant objects. *Binocular disparity* refers to the difference in viewpoint of the two eyes, a difference that diminishes exponentially as objects are farther from the viewer. *Stereopsis*, the use of binocular disparity to perceive depth, can occur in 3D displays when slightly different images are presented to the two eyes (Patterson, 1997). Some depth information is also obtained from *accommodation* and *binocular convergence*. These cues result from the natural adjustments of the eyes needed to focus on specific objects at different distances. Accommodation is the response of the lens required to bring very close objects into focus, and convergence is the "cross-eyed" viewing of the two eyes, also necessary to bring the image of closer objects into focus on the back of both retinas.

In viewing real 3D scenes, most of these depth cues operate redundantly and fairly automatically to give us very precise information about the relative distance of objects in the visual scene and adequate information about the absolute distance (particularly of nearby objects). Such distance judgments are also a necessary component of judgments of 3D shape and form. A host of research studies on depth perception reveal that the depth cues respond in a generally additive fashion to convey a sense of distance (see Wickens et al., 1989). Thus, as the viewer looks at a 3D display, the more depth cues that are available to the viewer, the more perceived separation there is between objects in depth (i.e., along the Z axis in 3D space).

Although all depth cues contribute to the sense of distance, there is evidence that three of those cues (i.e., motion parallax, binocular disparity, and interposition) are the most powerful and will dominate other cues when they are placed in opposition (e.g., Braunstein et al., 1986; Wickens et al., 1989, 2000). Hence, in designing a 3D display to synthesize the 3D spatial world, it is a good idea to try to incorporate at least one, if not two, of these dominant cues.

In constructing a 3D perceptual representation from a displayed or real 3D image, people may often be guided by knowledge-driven expectancies when interpreting the bottom-up distance cues. For example, the use of relative size as an effective cue depends on the viewer's assumption about the *true size* of the objects to be compared. If the assumptions are inaccurate, the use of relative size to judge distance can lead to illusions, sometimes dangerous ones. For example, Eberts and MacMillan (1985) concluded that the high rate of rear-end collisions suffered by small cars resulted from drivers' misuse of relative size. The trailing driver, seeing the smaller-than-expected retinal image of the small car, perceives the car to be of normal size and farther away. The perception of greater distance between cars, in turn, may lead to dangerously delayed braking.

Recent research indicates that reliance on other pictorial depth cues may lead to equally poor distance estimations on the part of drivers. Buchner et al. (2006) found that cars with higher backlights are at an increased risk of being perceived as more distant than they actually are. This illusion may be due to the misapplication of the depth cue that associates height in the picture plane with increased distance. Naturally, such illusions, based on inappropriate application of knowledge and expectancies, are more likely to occur when there are fewer depth cues available. This is why pilots are particularly susceptible to illusions of depth and distance (Previc and Ercoline, 2004), since many of the judgments they must make are removed from the natural coordinate framework of Earth's surface and must sometimes be made in the degraded conditions of haze or night.

Besides the problems of impoverished cues, a second problem with 3D displays is *line-of-sight ambiguity*. This is illustrated in Figure 7, which depicts a viewer looking into a volume containing three objects, A, B, and C, as we see the views from the side (top view). The view of these objects on the screen is shown below. Here we see that when the viewer makes judgments of position along the viewing axis into the 3D world, a given distance in the world is represented by a smaller visual angle than when judgments are made parallel to the display surface, a phenomenon known as *compression* (Stelzer and Wickens, 2006). In Figure 7 judgment of the distance AB along the Z axis is compressed, whereas the judgment of the distance AC_1 along the X axis is not. As a consequence of this reduced resolution along the viewing axis, it is harder to tell exactly how distant things are. This distance ambiguity, in turn, has repercussions for the ability to make precise spatial comparisons between objects in the plane orthogonal to the line of sight. Returning to Figure 5*a*, note how difficult it is to tell if the difference in height between the two distant bars is the same or different from the closer ones.

To make matters worse, it is often difficult in 3D displays to resolve the extent to which an object displaced to a new location is receding in depth or is moved to a higher location at the same depth, a further form of ambiguity. For example, the various movements of point C in Figure 7 to points C_1, C_2, and C_3 would all appear nearly equivalent to the viewer of the 3D display with few depth cues, since they all would occupy the same position along the line of sight into the display; the relative contribution of altitude to distance change would be difficult to resolve.

Of course, as we have noted, some of this ambiguity can be resolved in display viewing if the designer incorporates progressively more depth cues. Yet in many

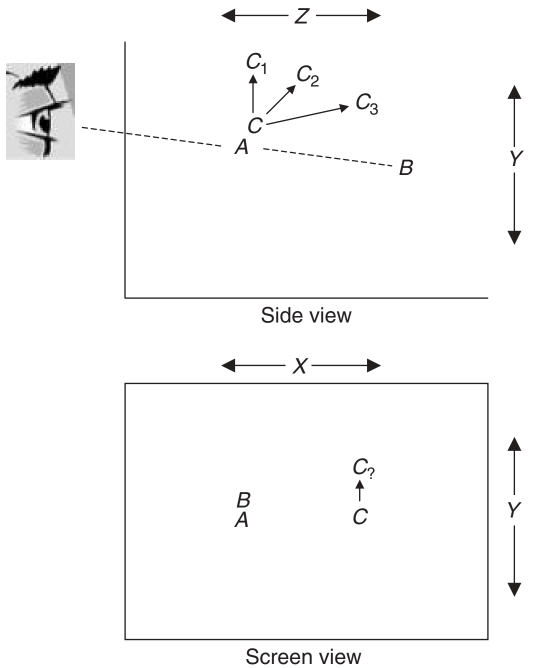

Figure 7 Ambiguity in 3D displays. The actual distance of objects A, B, and C from the observer is shown from the side, in the top view. The screen viewed by the observer is shown below. From the 3D screen view it may be ambiguous whether A or B is closer. Movement from *C* to C_1, C_2 and C_3 may all look identical.

circumstances it may be cumbersome or computer intensive to incorporate the most powerful cues of stereo and relative motion realistically; furthermore, there are certain tasks, such as those involved in air traffic control, precise robotic control, and some forms of minimally invasive surgery, in which the requirement for very precise spatial judgments with no ambiguity on any axis is so strong that a set of 2D displays, from orthogonal viewing axes, may provide the best option, even if they present a less natural or realistic view of the world (Wickens, 2000, 2003a).

Concerns for 3D ambiguity notwithstanding, the power of computers to create stereo and motion parallax rapidly and effectively continues to grow, thereby supporting the design of *virtual environments* that capture the natural 3D properties of the world. Such environments have many uses, as discussed in Chapter 40, and their creation must again make effective use of an understanding of the human's natural perception of depth cues. Further discussion of the benefits of different kinds of 3D displays for active navigation is provided in Section 5.4.2.

4.5 Motion Perception and Dynamic Displays

Although many of the displays discussed above are static, many other analog displays are frequently or continuously updated. Such displays have long been a part of air and ground transportation, process control, and manufacturing systems, and our ability to process motion cues is a requirement for our interaction with objects in both natural and virtual worlds. However, as with the perception of depth and 3D shape, the visual perception of motion can fall prey to a variety of illusions and ambiguities (Blake and Sekuler, 2006). Sometimes these perceptual distortions predispose operators to accidents, for example, the alarming tendency of drivers to cross railroads when trains are drawing dangerously close. Leibowitz (1985) has argued that this behavior may, in part, be due to a size-contingent distortion of speed. Specifically, we tend to see small objects as approaching faster than large ones, perhaps causing drivers to underestimate the speed at which trains, a large object by most vehicular standards, are approaching. Fortunately, errors of motion perception can sometimes be corrected by intentionally employing some of these same illusions, as we will see below. And most of us would agree that at least one motion illusion is of particular value as it is at the very core of many forms of communication and entertainment, that is, media that involve "moving" pictures.

Apparent motion is our ability to perceive seamless motion of displayed objects from a series of still images—as long as the individual images are presented within certain spatial–temporal bounds. Given over a century of experience with apparent motion, many of the parameters that affect this illusion are well known among animators and videographers as well as scientists (Hochberg, 1998). For example, an object is seen as moving smoothly from one location to another when presented in two successive pictures that are separated by approximately 20 m and when the displacement of the image is no more than approximately 15° of arc. Under these circumstances, the movement of an object usually appears to take the shortest path between its positions in the two frames. Although this process is mediated by relatively early, bottom-up processing, there is evidence that when intervals between images are long enough, apparent motion appears to be influenced by top-down factors such as the plausibility of the movement (e.g., a person's hand will be seen going over rather than through her head when the two successive images used to create apparent motion show a hand first on one side and then on the other side of her head; Shiffrar and Freyd, 1990).

Of importance to a variety of simulation and gaming applications is another motion illusion—*vection*, or the perception of self-motion by a stationary operator. The illusion of self-motion can be induced by visual displays that imitate the regularities in the pattern of flow of textures across the visual field as we change speed and trajectories in the natural world (Hettinger, 2002), thus taking advantage of some of the types of scene statistics we introduced when discussing context effects on recognition. In addition to their use to create perceptions of self-motion in virtual environments, relevant scene properties can be manipulated in the real world to alter operators' perceptions of self-motion in ways that can enhance safety. In order to encourage drivers to slow down when approaching a roadwork site, for example, researchers have found that placing a series of cones by the roadway can be helpful, especially when the spacing between the cones systematically decreases, giving drivers the illusory impression that they are accelerating (Allpress and Leland, 2010; also see Denton, 1980).

Further sources of uncertainty in motion judgments are *framework effects.* As a general rule, the visual perception of motion is greatly influenced by the framework within which it occurs. A very sparse display with few fixed reference elements, for example, can make it appear that a small, slowly moving display element is actually stationary. At the opposite end of the spectrum are situations where the target object is too big to be fully seen through the viewing framework. If there is uncertainty about the overall shape of the target object, the target may appear to move in a direction other than its true course. DeLucia et al. (2006) demonstrate the potential importance of this *aperture effect* during minimally invasive surgeries, where the view through the endoscope reveals only a very limited part of the surgical field, and the shape and location of various anatomical landmarks may be distorted by disease. The surgeon may make incorrect judgments about the location of the endoscope inside the patient because of an incorrect perception of its direction of movement based on the apparent flow of organs under the endoscope. This aperture effect can be reduced by using rectangular rather than round viewing windows, but its existence is one reason designers are pursuing the development of augmented displays that generate a computer model of the entire surgical field surrounding the immediate, detailed view from the endoscope (e.g., Wang et al., 2009).

Even when the motion of target objects in dynamic displays can be accurately perceived, operators may still have difficulty linking the motion or changes they perceive to the appropriate actions they should take. Thus, moving displays need to consider the compatibility of their changing elements with the mental models of their users (Gentner and Stevens, 1983; Norman, 1988). In the remainder of this section, we describe two general principles that can help designers match the elements of dynamic displays to users' expectations. The first of these is clearly applicable to both static and dynamic displays, although it may be more important in situations where users must quickly react to changing information. The second principle, however, deals with the meaning of motion itself in the context of the user's goals.

Code congruence requires that designers take into consideration users' expectations about the codes (i.e., stimulus dimensions) that should represent critical information. If a display is being designed to represent temperature, for example, then the use of a vertically moving bar might be an appropriate code because of mental models associated with mercury-based thermometers that often show temperatures "rising" and "falling." If we do choose this code, we must also be careful to map the values of the to-be-represented variable (temperature) to the display code in a way that conforms to users' experience. Thus, an increase in bar height should indicate hotter rather than colder temperatures.

In the preceding example, temperature is associated with vertical position through experience with thermometers rather than because there is anything inherently spatial about temperature. Many other variables, however, *are* spatial to begin with. In these cases, code congruence is maintained simply by using rescaled versions of the original spatial dimensions, making sure to orient the spatial model in a manner consistent with the typical viewpoint of the user. Thus, the temperature of different rooms in a building could be represented by superimposing our individual temperature displays on an actual plan view, elevation, or 3D view of the building. When the spatial metaphor is direct, as in this case, the display fulfills Roscoe's (1968) *principle of pictorial realism*.

Finally, in dynamic displays, the designer must be concerned with whether motion represented in a display is compatible with the movement expected by the operator. These expectations in turn are often driven by the *frame of reference* of display motion. As an example, a common design decision in systems involving robotics control is whether the camera generating a display of the moving robotics arm or vehicle should be mounted to the moving element itself (viewing the target to be reached) or to an external frame viewing the moving element. The difference between these two views is that when a control moves the element to the right, in the first case the display of the world slews to the left, whereas in the second case, the world is stable and the rightward control depicts rightward motion on the display. These two frames of reference are referred to respectively as (1) inside-out, moving world, or "ego referenced," and (2) outside-in, moving object, or world referenced.

There is some evidence that the second frame is better and more compatible (Johnson and Roscoe, 1972) in that it corresponds to what we naturally see when we view our hand as well as to the ecological perspective that the world is stable and objects move within it. However, it is also acknowledged that in many complex systems both views are needed, often the outside-in view for global positioning and the inside-out view for fine vernier control. What is most vital is to understand that it is possible for an operator to confuse the two if both are offered (simultaneously or sequentially). An operator viewing an inside-out view moves the control to the right with the intention of moving the object to the right; he or she suddenly sees a left movement on the display, perceives (incorrectly) it to be a control error, and quickly reverses the movement, now inadvertently creating such an error. This problem can be amplified if views are often switched between different modes.

4.6 Perceptual Organization, Display Organization, and Proximity Compatibility

Our discussion of motion highlighted how the *relationship* among displayed elements, in both time and space, can produce psychologically important effects such as apparent motion from still images. In this section, we look at how the relationship among component elements of multielement displays, such as those found in emergency management information systems, scientific visualizations, and process control workstations, can influence the effectiveness of these display systems, sometimes in dramatic ways.

The challenge for the designer of multielement displays is to determine how best to organize the various displays so that the natural laws of *perceptual organization* (e.g., Pomerantz and Kubovy, 1986; Hochberg, 1998) may support rather than hinder the user's acquisition of information. That is, we must take into account the laws by which our perceptual systems parse raw sensory data into potential targets for attention (e.g., perceptual parts, objects, and configurations). As noted in Section 3, multielement displays have the potential to create a variety of problems for the viewer, including increases in search time, increased information access effort, similarity-based confusion, and challenges to focused attention. Such concerns are becoming even more critical with the rapid evolution of expansive, high-definition displays (e.g., "data walls") to represent information for multiple concurrent tasks and users (Yost and North, 2006).

Many of the principles of display organization can be accounted for by the *proximity compatibility principle* (*PCP*) (Carswell and Wickens, 1987, 1996; Barnett and Wickens, 1988; Wickens and Andre, 1990; see Wickens and Carswell, 1995, for review). This is a broad-ranging principle with two parts: (1) when two (or more) elements of a display must be integrated (e.g., compared, multiplied, subtracted) in the service of a single task—a feature we describe as "close (or high) mental proximity"—they should be placed in close physical proximity on the display. However, (2) when one element must be processed by itself, without distraction from others (distant or low mental proximity requiring focused attention), its processing is best served when its display is more distant from its neighbors (low physical proximity). Hence there is a sort of "compatibility" between proximity in the mind and proximity on the display. Of course, what this means is that no single display layout serves all tasks, for what may be best for integration tasks ("how does my speed compare with a maximum speed allowable?") may not serve focused attention ("what is my current speed?").

The previous broad overview of the PCP is complicated by the fact that there are at least two kinds of "mental integration" (simple comparison and arithmetic combination, such as computing and amount from the product of rate and time) and a large number of ways of creating or manipulating "display proximity," as illustrated in Figure 8. The most obvious source of physical proximity is simple distance, as illustrated by rows (a) and (b) of the figure. Moving things closer together can minimize visual scanning; in a cluttered display, it can also minimize visual search for the two items to be compared, as attention must move from one to the other to compare them. From an information-processing perspective, the problem is often that information from one display must be held in vulnerable working memory as the other is sought. At a minimum, this dual-task requirement may produce a delay— a decay in the representation of the first item until the second is found. More severely, it may produce concurrent task interference (see Section 7) as an effort-consuming search must be carried out while information from the first display is rehearsed.

To cite extreme examples of low physical proximity, consider the challenge of comparing a picture on one page of a textbook to the text describing that picture on the back side of the same page. Would it not be better if text and picture were side by side so that repeated page flipping would not be needed? Instructional designers

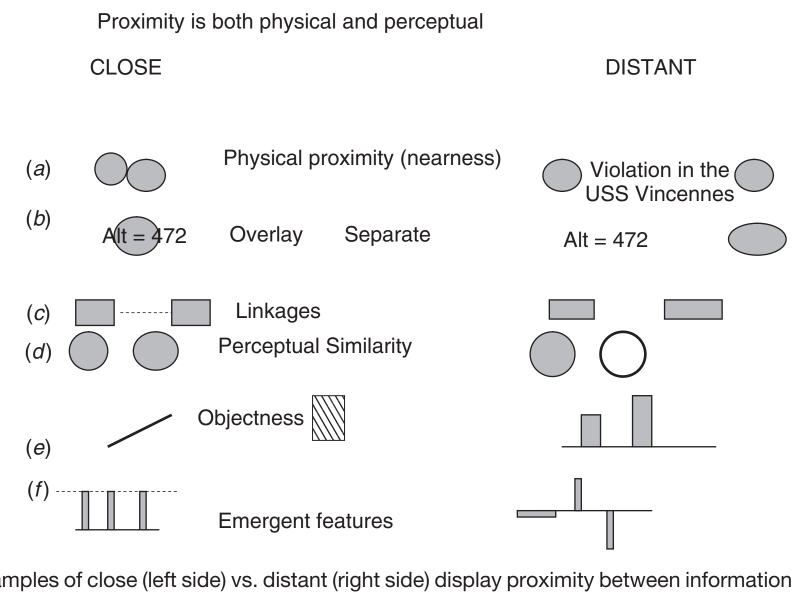

Figure 8 Six examples of close (left side) vs. distant (right side) display proximity between information sources influencing different perceptual mechanisms

need to consider the role of cognitive load of information integration in preparing their material (Paas et al, 2003). Or consider the problem of comparing a box legend on a graph labeling the multiple graph lines with the graph itself. It would be better if each graph line had its own label attached to it (Huestegge et al, in press) In this sense, display proximity can not only be conceptualized as physical distance affecting visual scanning but also includes the manual (and sometimes cognitive) effort required to "move" attention from one source to the other.

Row (b) of Figure 8 also illustrates the occasional downside of close physical proximity for focused attention. On the right, the oval indicator and the digital altitude reading are separated. It is easy to focus on one and ignore the other. On the left, they are overlaid. The very close physical proximity can create clutter, making it hard to focus on one and ignore the other. Such overlay is often created when viewing the world beyond through a head-mounted display (C. D. Wickens et al., 2004); such clutter of close proximity also may be created by overlaying computer windows (Mori and Hayashi, 1995). Of course, the reader may ask, "Can't we get the best of both worlds by placing the two indicators adjacent, and not overlapping?" and the answer here is "yes." Adjacency will greatly reduce the costs of integration, but if there is at least 1° of visual angle separating an item from its neighbors, this will pretty well minimize the costs to focusing attention.

Naturally, there are some circumstances in which displays simply cannot be moved to create adjacency or close proximity. In a cluttered demographic map, for example, two cities may be located at different places whose demographics (portrayed in icons, or text boxes) cannot be "relocated." As shown in row (c), linkages can achieve such physical proximity or "connectedness" (Jolicoeur and Ingleton, 1991). Indeed, in the simple line graphs, the lines connecting the data points are not essential to understanding the trends. But those lines, linking points belonging to the same condition, greatly assist graph interpretation. (As we will see below, the lines have another benefit for integration by creating emergent features.) Thus, if rendered appropriately, often in lower intensity, linkages can increase benefits to integration without imposing costs on focused attention.

When displays cannot be moved, an alternative to linkages, as shown in row (d), is to exploit perceptual similarity; for example, two items to be compared may be highlighted in the same color (as this *word* and the word in the paragraph below; L. D. Wickens, Alexander, et al., 2004) or may both be flashed or "jittered" in synchrony. This technique can be quite advantageous for an air traffic controller (ATC) who needs to consider the trajectories of two planes on the same altitude and converging but still far apart. On an ATC display cluttered with many other aircraft symbols, a highlighting tool (Remington et al., 2000) that can illuminate each in a common color can greatly reduce the demands of such a comparison.

In row (e) is depicted a conceptually different way of creating display proximity. Here a single object (in this case a line connecting two points on a line graph) is created to foster integration, whereas the more separated display shown on the right contains two objects (two bar graphs, or even three, if the baseline is considered). Basic research in attention describes how processing of all attributes of a single object can take place more or less in parallel, whereas processing two objects requires serial processing (and less efficiency; Treisman et al., 1983; Duncan, 1984; Scholl, 2007). In the graph shown in (e), not only is the single line more perceptually efficient to process, but also the slope of the line provides a direct indicator of the strength of the effect or trend, an indication that is easier to extract than by comparing the height of the two bars in the more separated display on the right (Carswell and Wickens, 1996; Hollands and Spence, 1992). We refer to this slope as one example of an *emergent feature* of the object display, a concept elaborated below.

There are of course many other ways of creating an object than just "connecting the dots." Shown just to the right of the word "objectness" in row (e) is a rectangle. This object has four features, its height, width, color, and texture, all conveyed within the confines of a single object. It would require four bar graphs (four objects) to convey all that information in separate displays. And object displays, if carefully configured, can be shown to greatly improve the facility of information integration (Barnett and Wickens, 1988). As a simple example, consider a demographic map. If each city were represented by four bar graphs, when several cities are closely packed together, the display would appear extremely cluttered, in contrast to the case where each is represented by a single rectangle.

Finally, row (f) of the figure illustrates a concept of display proximity that can also facilitate integration. Emergent features of the multiple elements of a display are created when the display is "configured" in such a way that a feature emerges from the combination of the elements (Buttigieg and Sanderson, 1991; Pomerantz and Pristach, 1989). In the close-proximity version on the left, the bar graphs are all aligned to the same baseline. Hence the emergent feature of "colinearity" is created when all bars are the same height (e.g., all of three engines of a machine are operating at the same power setting). In this configuration, it is quite easy to perform the mental integration task: "Is the power equally distributed?" Any break from this equality will be rapidly and easily perceived. In contrast, the configuration on the right will make the precise integration judgment of equality very challenging.

Referring back to row (e), we can see how, for example, the simple connections of endpoints to form a single object as in the line graph creates an emergent feature (line slope) that directly serves the integration task (how strong is the trend from left to right?). Also, creating an object like a rectangle display creates an emergent feature from its height and width: its area (the product of height and width) as well as its shape (tall skinny, short fat), which can often carry important information (Barnett and Wickens, 1988). But it is important to realize that not all dimensions of an object will configure in some geometric or spatial pattern: For example, color and height do not form an emergent feature (Carswell and Wickens, 1996). And of course, as row (f) illustrates, emergent features can readily be formed in the absence of the object display.

Regardless of whether emergent features are part of an object display or result from the configuration of separate objects, they can have potent effects on performance. We must caution that these effects are not always positive. Emergent features are *only* useful if they directly represent integrated variables or system states of importance to the operator. If they are irrelevant or, worse, cause patterns that cue responses inconsistent with those that are appropriate for safe and efficient system operation, the user may be better off with separable formats. Using the terms of Section 3, emergent features are salient and capture focused attention, whether wanted or not. *Representation aiding* is a display design approach in the cognitive engineering tradition (Section 2) that provides guidance on how to optimize the design of displays, including the use of emergent features (Vicente and Rasmussen, 1992; Smith et al., 2006). The focus of this approach is directly on understanding the physical constraints of dynamic systems and matching these to the geometric properties of configural formats in a way that is perceptually salient and meaningful to the operator. An example is shown in Figure 9.

Our discussion above has focused most heavily on the way in which close proximity supports information integration. But while we have identified separation (lower proximity) as a tool to support focused attention on a single element, lower proximity has a second benefit. That is, the close proximity and particularly the "binding" in an object display represent a designer-imposed solution to encourage the user to integrate particular subsets of information sources. However, such binding or grouping is not a "free lunch" for the viewer. If the viewer's task is not appropriately characterized by the designer, or if the task demands change, the viewer may need to "unbind" one or more elements from the perceptual group to use in a new way. The extra effort and reduced performance efficiency that occur in this situation may be considered a "parsing cost." This is what we experience when a graph's designer has not organized individual data points in a way that allows us to make the comparisons that are of most interest to us, instead forcing us to compare points across different perceptual groups (e.g., points on different lines or bars in different data series).

Clearly, the specific way in which a designer uses proximity tools in any display will make some integration tasks easy while imposing parsing costs on others. However, the designer's choices can also be used to infer their communication goals (or *graphical pragmatics*). Following this logic, there have been attempts to apply the PCP to the development of software that "reverses engineers" displays. That is, the software provides inferences to the user about the designer's underlying communication goals based on the way in which proximity is applied (Elzer et al., 2003). This information may, in turn, be used by viewers to help them decide if the display is likely to suit their information needs and to help automate the textural summary of graphical information for those individuals who cannot access the information visually. More generally, the

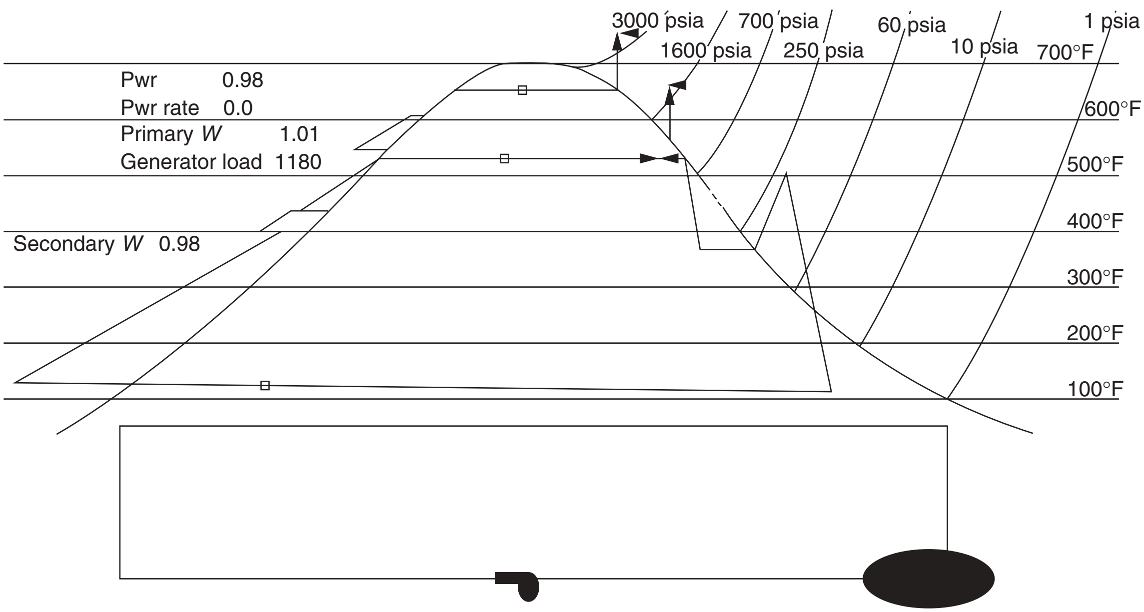

Figure 9 Rankine cycle display for monitoring the health of a nuclear power generating plant. The jagged line indicates the trajectory of the plant parameters (steam pressure and temperature) as they follow the constraints of the thermodynamic laws (proposed but not yet implemented for operational evaluation). (From Moray et al., 1994.)

study of graphical pragmatics highlights the extent to which individual, noninteractive visualizations, no matter how carefully designed, can impose on the viewer the designer's values and assumptions about what is meaningful in the displayed data. In particular, one may argue that in scientific or interpretive endeavors one of the most critical information-processing challenges is integrating data in a variety of different ways in order to obtain unique insights. Hence the importance of flexible data visualization tools that are not constrained by a particular designer's choices (Robertson et al., 2009; North, 2006), which can configure data in different ways, encouraging the use of different aspects of proximity.

In conclusion, forming effective multielement displays can sometimes be as much a creative "art" as it is a science. But effective use of different proximity tools can greatly facilitate information integration without necessarily compromising focused attention.

5 COMPREHENSION AND COGNITION

In our discussion of perception and display design, we have treated many of the operator's perceptual tasks as decision-making, problem-solving, or reasoning tasks. Detection involves decisions about criterion setting. Identification involves estimations of stimulus probabilities. Size and distance judgments in 3D space involve the formulation of perceptual hypotheses. For the most part, however, these processes occur rapidly and automatically, and as a result, we are generally not aware of them. In this sense, perceptual reasoning is a far cry from the effortful, deliberate, and often time-consuming process that we are very aware of when trying to troubleshoot a malfunctioning microwave, find our way through an unfamiliar airport, understand a legal document, or choose among several product designs. Before discussing such higher order cognitive tasks, we describe the critical limits of working memory. As we will see, the parameters of working memory constrain, sometimes severely, the strategies we can deploy to understand and make choices in many types of tasks.

5.1 Working Memory Limitations

Working memory refers to the limited number of ideas, sounds, or images that we can maintain and manipulate mentally at any point in time. The concept has its roots in William James's (1890) *primary memory* and Atkinson and Shiffrin's (1971) *short-term store*. All three concepts share the distinction between information that is available in the conscious here and now (working, short-term, or primary memory) and information that we are not consciously aware of until it is retrieved from a more permanent storage system (long-term or secondary memory).

Unlike items in long-term memory, items in working memory are lost rapidly if no effort is made to maintain them through rehearsal (Brown, 1959; Peterson and Peterson, 1959). For example, *decay rates* of less than 20 s have been obtained for verbally delivered navigation information (Loftus et al., 1979) as well as for visuospatial radar information (Moray, 1986). However, even when tasks require minimal delays before recall, working memory is still severely limited in its capacity. Miller (1956) suggested that this capacity, the *memory span*, is limited to about five to nine independent items. The qualifier "independent" is critical, however, because physically separate items that are stored together as a unit in long-term memory may be rehearsed and maintained in working memory as a single entity: a *chunk*. Thus, for most people, the letter string "H–T–E" contains three items to remember, whereas the rearranged string "T–H–E" contains only one.

Baddeley (2003) has integrated information about the limits described above with evidence from neuropsychological and psychometric investigations to develop a four-part model of working memory. First, there are two temporary storage systems, the *phonological loop* and *visuospatial sketchpad*. These subsystems are used by a *central executive* that manipulates information from these stores. The central executive also integrates information from the component storage systems with long-term memory to create more complex, multimodal representations of coherent objects. These integrated representations, in turn, are held in an *episodic buffer*. It should be noted that the proposed episodic buffer is a relatively recent addition to Baddeley's model (2000), which was originally conceptualized as having only three components (Baddeley and Hitch, 1974). Although relatively little is known about the limits of the episodic buffer compared to those of the phonological loop and the visuospatial sketchpad, the notion of a repository for objects of interest that is not limited to a single processing code is relevant to our discussions of virtually all higher order cognitive tasks.

Most research on the limits of working memory have focused on the *phonological loop*, so named because it is associated with our silent repetition or rehearsal of words, letters, and numbers. The phonological loop stores a limited number of sounds for a short period of time; thus, the number of items that can be held in working memory is related to the length of time it takes to pronounce each item (Gathercole and Baddeley, 1993; Gathercole, 1997). This implies that our memory span is slightly lower for words with many syllables.

The *visuospatial sketchpad* holds visual and spatial information as well as visualizations of information acquired verbally (Logie, 1995; Baddeley, 2003). The information held in the sketchpad may be in the form of mental images, and as with the phonological loop, the contents will be lost rapidly if not rehearsed. Research suggests that rehearsal in the visuospatial sketchpad involves repeated switching of selective attention to different positions across these images (Awh et al., 1998). The proposed maintenance function of attention switching may explain why our control of eye movement apparently disrupts some contents of the sketchpad (Postle et al., 2006).

The central executive is aptly named because its functions can be compared to those of a business executive. The central executive's role is not to store information but to coordinate the use of information. This information may come from the phonological loop, the visuospatial sketchpad, or the episodic buffer. The central executive is presumed to be involved in integrating information from these different stores, and it is also involved with selecting information, suppressing irrelevant information, coordinating behavior, and planning (see Section 5.5 for the relevance of these functions for problem solving). It is important to note that there are limits on how many of these operations the central executive can execute at one time.

The concept of working memory has a number of implications for design. We describe some of these implications below, and in subsequent sections we discuss other implications for higher order tasks such as decision making, problem solving, and creative thinking.

1. The capacity of working memory's short-term storage systems are easily exceeded, resulting in a loss of information that may be necessary to perform an ongoing task (consider rehearsing a 10-digit phone number and area code). The design implication is to avoid, whenever possible, codes that infringe on the limits of these systems.
2. When it is necessary to use codes that exceed the limits of working memory capacity, there are several ways to reduce memory loss. For example, parsing material into three- or four-item units may increase chunking and subsequent recall (Wickelgren, 1964). Thus, 3546773 is more difficult to recall than 354–6773. In addition, information for different tasks may be split between storage systems so that a single system, for example, the visuospatial sketchpad, is not overwhelmed. More will be said about such interventions when we turn to the discussion of multitask performance (see Section 7). Finally, designers should prefer easily pronounced verbal codes. For example, numerical codes that make frequent use of the two-syllable number "seven" will be more prone to loss from the phonological loop than codes that make frequent use of other numbers. It may also suggest that the functional number span for some languages may be larger than those for others.
3. Information from working memory may be lost if there are delays longer than a few seconds between receiving the information and using it. Thus, systems should not be designed so that the user must perform several operations before being able to perform a "memory dump." For example, voice menu systems should always allow users to select a menu option as soon as it is presented rather than forcing them to wait until all the options have been read to make their choice. Methods of responding should be simplified as well, so that users do not have to retain their choice for long periods of time while trying to figure out how to execute it. One aspect of the proximity compatibility principle (Section 4.6) emphasizes working memory limitations on the need to seek a second source of information to be integrated while rehearsing the contents of the first source.
4. The need to scan should be minimized if a person must hold spatial information in the sketchpad. Thus, a first responder who has found the likely location of a victim in cluttered, unfamiliar, and distorted terrain should not have to scan long lists of information to find appropriate communication codes.
5. Avoid the need to transfer information from one subsystem into the other before further transformations or integrations can be made. This reduces the resources available for the primary processing goal. Wickens et al. (1983, 1984) have provided evidence that the display format should be matched to the working memory subsystem that is used to perform the task. Specifically, visual-analog displays are most compatible with tasks utilizing the visuospatial sketchpad (e.g., air traffic controllers' maintenance of a model of the spatial relations among aircraft) and auditory–verbal displays are most compatible with tasks utilizing the phonological loop (e.g., a nurse keeping track of which medications to administer to a patient).
6. If working memory subsystems are updated too rapidly, old information may interfere with the new. For alphanumerical information, Loftus et al. (1979) found that a 10-s delay was necessary before information from the last message no longer interfered with the recall of the current material. As we will see below, when such updating occurs nearly continually, the capacity of working memory is greatly reduced to around its "$7 - 2 = 5$" value.
7. Interference in working memory is most likely when to-be-remembered information is similar in either meaning or sound. Thus, an air traffic controller might have particular difficulties remembering a series of aircraft with similar call signs (UAL 235, UAL 325). Interference will also be greater if there is similarity between material to be remembered and other competing tasks (i.e., listening, speaking) (Banbury et al., 2001).
8. The capacity of working memory varies between people and has been associated with differences in the fluency of the central executive and hence with success in multitasking and general intelligence (Engle, 2002; Engle et al., 1999).

5.2 Dynamic Working Memory, Keeping Track, and Situation Awareness

Much of the research devoted to working memory has examined tasks in which information is delivered in discrete batches and the goal is to remember as much of the information as possible. However, there are many other tasks in which the operator must deal with continuous information updates with little expectation of perfect retention. Moray (1981) studied several *running memory tasks* that simulated the demands of a more continuous input stream, and he found the typical memory span to be less than five chunks. In some cases it was difficult for subjects to keep track of items more than two places back in the queue. Yntema (1963) demonstrated that the way information is organized has a direct impact on supervisors' abilities to keep track of values of multiple attributes of several objects (e.g., status and descriptions of several aircraft). Supervisors had greater success keeping track of a few objects that varied on many different (and discriminable) attributes than in keeping track of variation in a few attributes for many objects. In the former case there are fewer opportunities for confusion than in the latter case, and confusion is a major source of disruption in working memory (Hess and Detweiler, 1995).

This earlier research on running memory anticipates the rapid growth of interest over the last two decades in *situation awareness* (SA) or, colloquially, our understanding and use of information about "what's happening" during dynamic tasks (Wickens, 2008; Tenney and Pew, 2006; Banbury and Treselian, 2004; Endsley and Garland, 2000; Durso et al., 2007; see also Chapter 19). Endsley (1995) provides a more formal definition of SA, one that has been adopted by many current researchers: SA is "... the perception of the elements of the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." This definition suggests that SA has three stages or "levels": (1) perception or "noticing," (2) understanding or comprehending, and (3) projecting or prediction. These three levels of situation awareness can be tied directly to different aspects of information processing and, therefore, failures at different levels will require different types of training or design interventions.

Stage 1 SA, noticing, traces directly to issues of selective attention and attentional capture, discussed in Section 2. Indeed, Jones and Endsley (1996) found that a majority of aircraft accidents attributable to loss of SA were related to breakdowns at this first stage. Likewise, Durso et al. (2007) found failures of stage 1 SA to be responsible for many SA-related problems encountered in air traffic control. This is not surprising given our previous discussion of how easily we can fail to notice significant changes in dynamic systems (e.g., the "change blindness" phenomenon; see Section 3.1). In general, failures of stage 1 SA typically indicate the need for interventions involving display design, especially the use of alerts and attentional cueing. However, because sampling of information in dynamic environments also involves long-term memory in the form of knowledge about "where and when to look," training interventions may also be considered (e.g., Hoffman et al., 1998).

Stage 2 SA, understanding the implications of events noticed in stage 1, depends heavily on the limits of working memory as they apply to keeping track of evolving situations (e.g., the pilot asks: "Where was that traffic aircraft the last time that I looked?"). The episodic buffer of working memory proposed by Baddeley (2003), with its connections to long-term memory, may be necessary to explain the ability of skilled performers to hold more information for longer periods than would be expected on the basis of the decay rates established for other working memory stores. Likewise, Ericsson and Kintsch (1995) have used the concept of *long-term working memory* with its automatic activation of relevant knowledge structures in long-term memory to explain the unusual ability of experts to maintain and integrate relatively large amounts of information across time. For operators who may lack extensive experience, and even for experienced operators who may be interrupted by other tasks, displays of system history may also be helpful in understanding the implications of current events in light of prior observations (St. John et al., 2005).

The stage 3 component, prediction and projection, is perhaps the most complex and may depend to a greater extent than the other two stages on the expertise and training of the operator. Accurate prediction of an evolving situation certainly depends on current perception and understanding (stages 1 and 2), but it also requires a well-calibrated *mental model* of the dynamic process under supervision (Gentner and Stevens, 1983; Wilson and Rutherford, 1989), a mental model that can be "played" in response to the current data, in order to predict the future state. For example, an air traffic controller with a good mental model of aircraft flight characteristics can examine the display of the current state and turn the rate of an aircraft and project when (and whether) that aircraft will intersect a desired approach course, thereby attaining a satisfactory separation. A well-calibrated mental model resides in long-term memory, but to play the model with the current data requires perception of those data as well as the active cognitive operations carried out in working memory. In some cases, prediction can be approximated by using an expert acquired *script* of the way a typical situation unfolds. However, unless active processing (stage 1) of incoming perceptual information is carried out, there is a danger that projection will be based totally on expectancies of typical situations and that unusual or atypical events will be overlooked. Naturally, stage 3 SA can benefit greatly from accurate predictive displays (Wickens et al., 2000).

It should be noted, finally, that situation awareness is a construct that is resident within the perceptual–cognitive operations of the brain. It is not itself a part of the action (other than the actions chosen to acquire new information).

5.3 Text Processing and Language Comprehension

Comprehension of language, whether written or spoken, shares many of the processes described for situation awareness. Noticing relevant information, understanding its implications, and to varying degrees projecting the content of upcoming messages are all part of the active process of language comprehension. The constraints relevant to information processing at each of these stages helps determine why we find some conversations, lectures, journal articles, instructions, and warnings easier to understand than others.

Of course, factors influencing the detectability and discriminability of the individual speech sounds (phonemes) and written symbols (letters) will limit the extent to which language can be processed meaningfully. However, recall that easily comprehended phrases or sentences can also influence the detectability of the individual words. See Section 3.2 for a discussion of the effect of context on identification. We are typically able to understand sentences such as the last one despite the absence of many of the correct letters in the words, because of the profound effects of context, expectancies, and the redundancies inherent in language. It is worth noting that just as context can help us recognize familiar words; it can also help us understand the meanings of words that we have never encountered before (Sternberg and Powell, 1983).

As our discussion of context suggests, the comprehensibility of text depends on many factors, from the reader's experience, knowledge, and mental models that drive expectations to the structuring of text so as to make maximum use of these expectancies. It is not surprising, then, that *readability metrics* that attempt to estimate the difficulty of text passages, generally based on average word and sentence length, are not altogether satisfactory. Although it may be true that longer words are generally less familiar and longer sentences place greater demands on our working memory capacities, many other factors influence comprehensibility. Kintsch and Vipond (1979), for example, used traditional readability indices to compare the speeches of candidates in the 1952 presidential campaign. Eisenhower's speeches were generally reputed to be simpler than those of Stevenson, yet formal readability indices indicated that Stevenson used shorter words and sentences. This contradiction between public opinion and the formal metrics corresponds to our experience that some sentences with a few short words can still be very confusing. We now discuss some additional factors that determine comprehensibility and have implications for message design.

Kintsch and colleagues (e.g., Kintsch and Keenan, 1973; Kintsch and Van Dijk, 1978) argue that the complexity of a sentence is actually determined by the number of underlying ideas, or *propositions*, that it contains rather than by the number of words. Although a few specific words may be carried forward in working memory for brief periods, it is the underlying propositions that are used to relate information in different phrases and sentences. Just as Moray (1981) estimates that running memory carries forward less than five chunks of information, Kintsch and Van Dijk (1978) estimate that only four propositions can be held in working memory at one time. There are some exceptions to this general rule, as when a highly skilled reader reads text on a very familiar topic. As we saw in our discussion of situation awareness, the memory effects of such expertise have led some to argue for the existence of a long-term working memory in which long-term memory associations are automatically activated and used during ongoing comprehension at little additional processing cost. However, as a general rule, readers must be very selective in their choices of propositions to retain, usually favoring the most recent propositions and those they believe to be most central to the overall text message.

Problems arise in comprehension when newly encountered propositions cannot easily be related to the propositions active in working memory. Such problems often occur when readers attempt to integrate information across sentence boundaries. Consider, for example, the following sentences:

1. When the battery is weak, a light will appear.
2. You will see it at the top of the display panel.

Readers must make the *bridging inference* that the second sentence is telling them where to look for the light rather than where to find the battery. This inference, in turn, depends on their general knowledge of displays: Lights rather than batteries tend to be visible on display panels. A second type of integration failure occurs when a concept introduced earlier in the text is not actually used again until some sentences, paragraphs, or pages later. In fact, even relatively minor delays, such as the need to scroll in order to see additional text on a web page, can lead to comprehension decrements, especially in readers with smaller working memory capacities (Sanchez and Wiley, 2009). Such challenges to text comprehension are often explained by the need to conduct a *reinstatement search*, which requires an effortful search of long-term memory or a rereading of earlier text, in order to clarify the meaning of a proposition in current working memory.

One general goal in striving for comprehensibility is to avoid the need to make bridging inferences or perform reinstatement searches. However, it is clearly impossible to remove the need to make some inferences, and it is probably undesirable given that such elaborations may make the information more memorable. One goal of the text designer is simply to assist the reader in making the *appropriate* inferences. One important way that this can be done is by providing adequate context immediately prior to the presentation of target information (McKoon and Ratcliff, 1992). Because inferences draw on the reader's knowledge of particular topics, it is useful to allow the reader to access the relevant knowledge structures in long-term memory at the outset. Bransford and Johnson (1972) provide a powerful demonstration of the importance of providing context in the form of pictures or descriptive titles presented just prior to textual material. A series of instructions on how to wash clothes was presented with and without the prior context of a title, "washing clothes." When the title was removed, the reduction in readers' abilities to understand and recall the instructions was dramatic.

Other factors that increase the processing demands of verbal material include the use of negations and lack of congruence between word orders and logical orders. With regard to negations, research indicates that it takes longer to verify a sentence such as "the circle is not above the star" compared to "the star is above the circle" (Clark and Chase, 1972; Carpenter and Just, 1975). Results suggest further that the delay is due to something other than the time necessary to process an additional word (i.e., "not"). Instead, it appears that listeners or readers first form a representation of the objects in the sentence based on the order of presentation (e.g., circle-before-star in the sentence "the circle is not above the star." However, to make their mental representation congruent with the meaning of the negation, they must perform a transformation of orders (i.e., to end up with a circle that is *not* before/above the star). Similar logic is used to explain why we have trouble processing statements in which there is a mismatch between the underlying logical order and the actual, physical order of the words (DeSoto et al., 1965). Returning to our battery of instructions once again, the underlying causal sequence assumed by most people would be that a weak battery would trigger a warning light. To be consistent with this causal order, it would be better to state that "If the battery is weak, the light will come on" rather than "If the light comes on, the battery is weak."

Finally, the physical parsing of sentences on a page, sign, or computer screen can also influence the comprehensibility of verbal messages. Just and Carpenter (1987) have argued that readers pause and integrate propositions at the end of each phrase in a sentence. This idea may explain why comprehension of sentences that must be split over multiple lines is better when the end of each line of text corresponds to the end of a constituent phrase (Graf and Torrey, 1966). Thus, instructions or warnings that must appear on several different lines (or as a few words on several successive screens) should be divided by phrases rather than, for example, on the basis of the number of letters. "Watch your step . . . when exiting . . . the bus" will be understood more quickly than "Watch your . . . step when . . . exiting the bus."

5.4 Spatial Awareness and Navigation

Language comprehension sometimes taxes working memory, particularly the phonological rehearsal loop and central executive. However, as we saw when discussing problems with negation, people may use text to generate representations of spatial relations. This spatial facet of text and language comprehension has been particularly prominent in recent discussion of the "situation models" that we develop when reading or listening to a story (e.g., knowing where in a room all the characters are sitting). We now turn to a task that relies more heavily, for many people, on the capacity limits of the visuospatial sketchpad (Logie, 1995) or, more generally, spatial working memory and spatial cognition (Shah and Iyiri, 2005)—navigating through our worlds, both real (finding our way through a maze of looping suburban streets and cul-de-sacs; Taylor et al., 2008) and virtual (searching a complex computer-displayed multidimensional database; Wickens et al., 2005).

5.4.1 Geographical Knowledge

Thorndyke (1980) has studied the knowledge that people use when finding their way about. Of particular interest is Thorndyke's claim that increased familiarity with an area causes changes in more than the amount of detail contained in our mental representation of that area stored in long-term memory. In addition, the actual *type* of mental representation (analog versus verbal/symbolic), as well as its frame of reference, may evolve in a predictable way. After an initial encounter with a city, neighborhood, or building, we may develop *landmark knowledge*. If told that his or her destination is beside the "telephone tower," a person with landmark knowledge will scan the environment visually until spotting something that appears to be the tower and will then strike off in its direction. Thus, the newcomer has the knowledge necessary to recognize the landmark but has no knowledge about its location. For the person with landmark knowledge alone, wayfinding would be impossible if the landmarks were obscured. This problem has become commonplace as once-salient landmarks have become obscured by new and often taller structures. The problem for urban planners, then, is to ensure that landmarks (both natural and designed) remain easily visible and distinctive in order to serve their navigational function for years to come.

With more experience traveling about an area, we typically develop an ordered series of steps that will get us from one location to another. These sets of directions, called *route knowledge*, tend to be verbal in nature, stated as a series of left–right turns (e.g., "Go left on Woodland until you get to the fire station. Then take a left . . . "). Navigation along these routes may be rapid and very automatic; however, limited knowledge of the higher order relations among different routes and landmarks still limits navigational decision making, making it difficult, for example, to figure out shortcuts and particularly difficult to recover when lost. With still more extensive wayfinding experience, or with specific map study, *survey knowledge* may be acquired. Survey knowledge is an integrated representation of the various routes and landmarks that preserves their spatial distance relations. This analog representation is often referred to as a *cognitive map*.

The type of representation—route versus survey—that best supports performance in various wayfinding tasks, like so many other aspects of mental (and display) representation, depends on the nature of the task or problem. Thorndyke and Hayes-Roth (1982) compared *route training* (actual practice navigating between specific points in a large building) to *survey training* (study of the building map). Route training appeared to facilitate people's estimates of route distance and orientation, while survey training appeared to facilitate judgments of absolute (Euclidean) distance and object localization.

5.4.2 Navigational Aids

Although we can often navigate through environments on the basis of our acquired knowledge stored in long-term memory, whether route, survey, or even landmark, there are many other circumstances in which we require displayed *navigational aids* which are perceived. These aids may take on a wide variety of forms, ranging in the degree to which guidance to a target is supported: from tightly guided flight directors in aircraft and turn signs on highways to route lists to electronic maps that highlight one's current position to simple paper maps. Furthermore, electronic maps can vary in the extent to which they rotate so that the direction of travel is "up" on the map, and both electronic and paper maps can vary in terms of whether they present the world in planar or 3D perspective view as the latter is seen in many in-car navigation displays (see Section 4.4).

To understand which forms of maps support the best spatial information processing to accomplish navigation, it is important to consider briefly the stages involved in this process. The navigator must engage in some form of visual search of both the navigational aid (to locate the final destination, intermediate goals, and current location) and the environment or a displayed representation thereof (to locate landmarks that establish the current location and orientation). The navigator must then establish the extent to which the former and the latter are congruent, determining the extent to which "where I am" (located and oriented) agrees with the intermediate goal of "where I want to be." Finally, the traveler must choose an action (e.g., turn right) to move from the current location toward the goal. Establishing this congruence as well as choosing the action may require any number of different *cognitive transformations* that add both time and effort to the navigational task (Aretz, 1991; Hickox and Wickens, 1999; Gugerty and Brooks, 2001; Wickens et al., 2005, 2010).

An example of two of these transformations is represented in Figure 10, which represents the information processing of a pilot flying south through an environment depicted on a north-up contour map. To establish navigational congruence, the pilot must rotate the map mentally to a track-up orientation and then envision the contour representation of the 3D terrain to determine its congruence with the forward view. Both of these information transformations are effortfuland time consuming and provide sources for error. In particular, those sources involved with mental rotation of maps have been well documented (Levine, 1982; Eley, 1988; Warren et al., 1990; Aretz, 1991; Olmos et al., 1997; Gugerty and Brooks, 2001; Macedo et al., 1998.

Different transformations may be required when other navigational aids than the 2D map are provided. For example, verbal descriptions of landmarks will also require some transformations to evaluate against their visible 3D spatial counterparts. Transformations may also be required to "zoom in" to a large-scale map (Kosslyn, 1987) in order to establish its congruence with a close-in view of a small part of the environment. Modeled in terms of processing operations such as visual search and spatial transformations, one can then determine the form of navigational aids that would be of benefit for certain tasks. For example, electronic maps are beneficial if they highlight the navigator's current location, thus obviating visual search of the map. Highlighting landmarks on the map, which are salient in the visual world, will correspondingly reduce search.

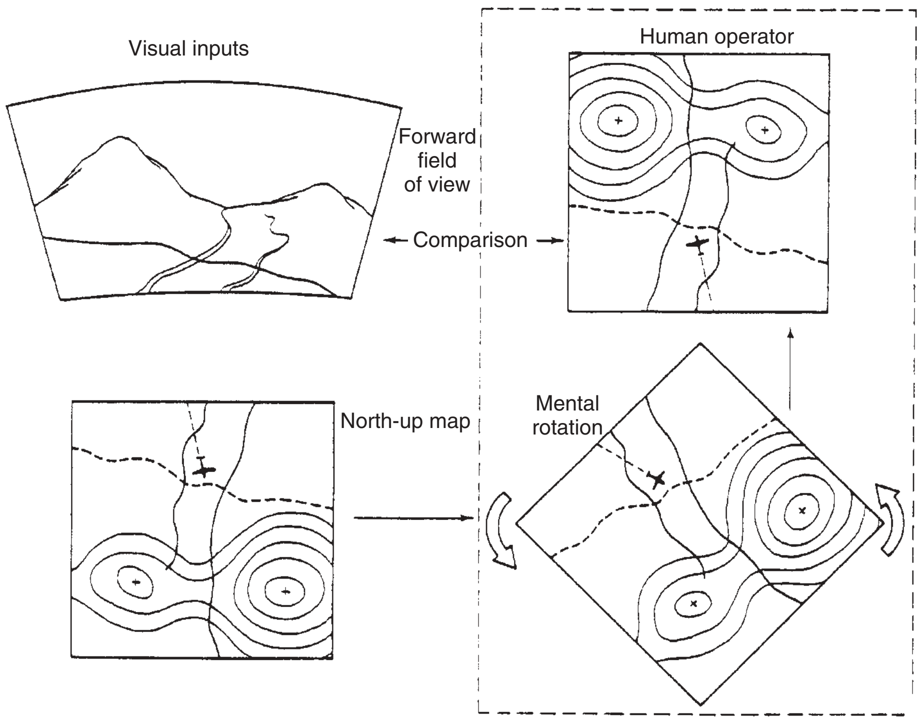

Figure 10 Mental rotation required to compare the image seen in an ego-referenced forward field of view (top) with a world-referenced north-up map (below) when the aircraft is heading south. The map image is mentally rotated (right) to bring it into lateral congruence with the forward field of view. It is then envisioned in three dimensions to compare with the forward field of view.

Rotating maps in a track-up orientation will help navigation by eliminating mental rotation (Aretz, 1991; Olmos et al., 1997; Wickens, 1999). Presenting guidance information in a 3D format (Section 4.4), like one would see looking ahead into the environment itself, will also reduce the magnitude of any sort of transformations and considerably improve navigational performance (Wickens and Prevett, 1995; Wickens et al., 2005). The benefits of a 3D view will be enhanced if the viewpoint of the display corresponds to the same zoom-in viewpoint as that occupied by the navigator, looking forward, rather than a viewpoint that is behind and from the outside (Wickens and Prevett, 1995; Prinzel and Wickens, 2008–2009). These viewpoint relationships are shown in Figure 11, which depicts the viewpoint location (top) and the view seen by a pilot (bottom row) in an immersed or *egocentric view* (*a* and *b*). (These two views differ in terms of their geometric field of view.) Panel (*c*) represents an external or exocentric view. Panel (*d*) represents a 2D coplanar view, which was discussed in Section 4.4.

Expressing navigational guidance in terms of command *route lists* (e.g., “turn left at X; go three blocks until Y”) will also eliminate the need for many of the spatial cognitive transformations that may be imposed when spatial maps are used, since the language of command is thereby expressed directly in the language of action. Such congruence can account for the benefits of route lists over spatial maps in certain ground navigation tasks (Streeter et al., 1985). A second advantage to such route lists is that they can be presented verbally and represented in working memory mentally in a phonetic or verbal code, thus reducing competition for the spatial processing resources involved in many aspects of environmental scanning and vehicle navigation (Section 7). The verbal descriptions inherent in route lists are well suited for some navigational environments, particularly human-designed environments (cities) with objects that are easily labeled, have distinct unambiguous landmarks, and can easily be discriminated by counting (the “fourth house”). In many naturalistic environments, however, where features are defined by continuous, not categorical, properties and may be confusable, route lists are more problematic and should be coupled with redundant spatial or pictorial guidance.

The most direct levels of navigational guidance that eliminate most or all levels of mental transformations (e.g., a flight director, the 3D forward-looking display shown in Fiigure 11*a*, or a verbal route list) will provide for effective navigation while en route. However, such displays may do a disservice to the navigator who suddenly finds himself lost, disoriented, or required to make a spontaneous departure from the planned route. Also, those features that make a navigational display best for guidance will harm its effectiveness to support the spatial situation awareness (Section 5.2) that is necessary for a successful recovery from a state of geographical disorientation (Wickens and Prevett, 1995; Wickens, 1999). This is an important trade-off between the immersed 3D view of Fiigure 11*a*, which is good for guidance, but because of its “keyhole view” of the world, it is poor for maintaining global situation awareness, a task better supported by the exocentric view of Fiigure 11*c*. Finally, we note that the immersed 3D view makes a poor tool for route planning, an activity that we turn to in the following section.

5.5 Planning and Problem Solving

Our previous discussion has focused on cognitive activities that were heavily and directly driven by information in the environment (e.g., text, maps, or material to be retained in working memory). In contrast, the information-processing tasks of planning and problem solving are tied much less directly to perceptual processing and are more critically dependent on the interplay between information available in (and retrieved from) long-term memory and information-processing transformations carried out in working memory.

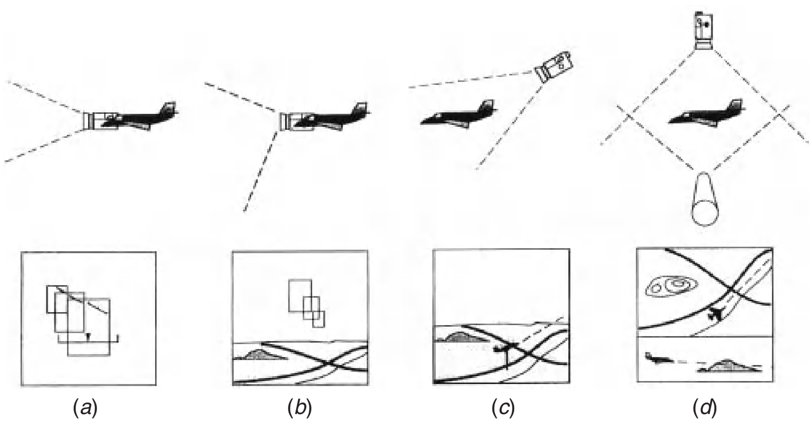

Figure 11 Display viewpoints in an aircraft display that require varying degrees of transformations to compare with a pilot’s direct view forward from the cockpit, looking at a virtual ‘‘highway in the sky’’ The lower figures illustrate schematically what would be seen by the pilot with the viewpoint shown above. The transformation in (*a*) is minimal; in (*b*) and (*c*), modest; and in (*d*), large. Views (*a*) and (*b*), however, reduce more global situation awareness.

5.5.1 Planning

The key to successful operation in many endeavors (Miller et al., 1960) is to develop a good plan of action. When such a plan is formulated, steps toward the goal can be taken smoothly without extensive pauses between subgoals. Furthermore, developing contingency plans will allow selection of alternative courses of actions should primary plans fail. As an example, pilots are habitually reminded to have contingency flight plans available should the planned route to a destination become unavailable because of bad weather.

Planning can typically depend on either of two types of cognitive operations (or a blend of the two). Planners may depend on scripts (Schank and Abelson, 1977) of typical sequences of operations that they have stored in long-term memory on the basis of past experience. In essence, one's plan is either identical to or involves some minor variation on the sequence of operations that one has carried out many times previously. Alternatively, planning may involve a greater degree of guess work, and some level of mental simulation of the intended future activities (Klein and Crandall, 1995; see Chapter 37). For example, in planning how to attack a particular problem, one might play a series of "what-if" games, imagining the consequences of action, based again on some degree of past experience. Hence a surgeon, in planning how to manage a potential future operation, might mentally simulate the future body conditions and reactions of the patient under different proposed surgical procedures to see if the intended commands would resolve the conflict and would stay clear of other aircraft.

Consideration of human performance issues and some amount of experimental data reveals three characteristics of planning activities. First, they place fairly heavy demands on working memory, particularly as plans become less script based and more simulation based. Hence, planning is a task that is vulnerable to competing demands from other tasks. Under high-workload conditions, planning is often the first task to be dropped, and operators become less proactive and more reactive (Hart and Wickens, 1990). The absence of planning is often a source of poor decision making (Orasanu, 1993; Orasanu and Fischer, 1997). Second, perhaps because of the high-working-memory demands of planning, in many complex settings, people's *planning horizon* tends to be fairly short, working no more than one or two subgoals into the future (Tulga and Sheridan, 1980). To some extent, however, this characteristic may be considered as a reasonably adaptive one in an uncertain world, since many of the contingency plans for a long time horizon in the future would never need to be carried out and hence are probably not worth the workload cost of their formulation. Finally, given the dependency of script-based planning on long-term memory, many aspects of planning may be biased by the *availability heuristic* (Tversky and Kahneman, 1974; Schwarz and Vaughan, 2002), discussed in more detail in Chapter 8. That is, one's plans may be biased in favor of trajectories that have been tried with success in the past and therefore are easily recalled.

Consideration of such vulnerabilities leads inescapably to the conclusion that human planning is a cognitive information-processing activity that can benefit from automated assistance, and indeed, such planning aids have been well received in the past for activities such as flight route planning (Layton et al., 1994) and industrial scheduling (Sanderson, 1989). Such automated planners provide assistance that need not necessarily replace the cognitive processes of the human operator but merely provide redundant assistance to those processes in allowing the operator to keep track of plausible courses of future action.

5.5.2 Problem Solving, Diagnosis, and Troubleshooting

The three cognitive activities of problem solving, diagnosis, and troubleshooting all have similar connotations, although there are some distinctions between them. All have in common the characteristic that there is a goal to be obtained by the human operator; that actions, information, or knowledge necessary to achieve that goal is currently missing; and that some physical action or mental operation must be taken to seek these entities (Mayer, 1983; Levine, 1988). To the extent that these actions are not easy or not entirely self-evident, the processes are more demanding.

Like planning, the actual cognitive processes underlying the diagnostic troubleshooting activities can involve some mixture of two extreme approaches. On the one hand, situations can sometimes be diagnosed (or solutions to a problem reached) by a direct match between the features of the problem observed and patterns experienced previously and stored in long-term memory. Such a *pattern-matching technique*, analogous to the role of scripts in planning, can be carried out rapidly, with little cognitive activity, and is often highly accurate (Rasmussen, 1981). This is a pattern of behavior often seen in the study of *naturalistic decision making* (Zsambok and Klein, 1997; Kahneman and Klein, 2009; see Chapter 8).

At the other extreme, when solving complex and novel problems that one has never experienced before, a series of diagnostic tests must often be performed, their outcomes considered, and based on these outcomes, new tests or actions taken, until the existing state of the world is identified (diagnosis) or the problem is solved. Such an iterative procedure is typical in medical diagnosis (Shalin and Bertram, in press). The updating of belief in the state of the world, on the basis of the test outcomes, may or may not approach prescriptions offered by guidelines for *optimal information integration*, such as Bayes's theorem (Yates, 1990; see Chapter 8).

In between these two extremes are hybrid approaches that depend to varying degrees on information already stored in long-term memory on the basis of experience. For example, the sequence of administering tests (and the procedures for doing so) may be well learned in long-term memory even if the outcome of such tests is unpredictable and must be retained or aggregated in working memory. Furthermore, the sequence and procedures may be supported by (and therefore directly perceived from) external *checklists*, relieving cognitive demands still further. The tests themselves might be physical tests, such as the blood tests carried out by medical personnel, or they may involve the same mental simulation of what-if scenarios that was described in the context of planning (Klein et al., 1993).

As with issues of planning, so also with diagnosis and problem solving, there are three characteristics of human cognition that affect the efficiency and accuracy of such processes. First, as these processes become more involved with mental simulation and less with more automatic pattern matching, their cognitive resource demands grow and their vulnerability to interference from other competing tasks increases in a corresponding fashion (see also Chapter 9). Second, as we noted, past experience, reflected in the contents of long-term memory, can often provide a benefit for rapid and accurate diagnosis or problem solutions. But at the same time, such experience can occasionally be hazardous, by trapping the troubleshooter to consider only the most *available* hypotheses: often those that have been experienced recently or frequently and hence are well represented in long-term memory (Tversky and Kahneman, 1974; Schwarz and Vaughn, 2002). In problem solving, this dependence on familiar solutions in long-term memory has sometimes been described as *functional fixedness* (Adamson, 1952; Levine, 1988).

Third, the diagnostic/troubleshooting process is often thwarted by a phenomenon referred to alternatively by such terms as *confirmation bias* and *cognitive tunneling* (Levine, 1988; Nickerson, 1998; Woods et al., 1994; Wickens and Hollands, 2000). These terms describe a state in which the troubleshooter tentatively formulates one hypothesis of the true state of affairs (or the best way to solve a problem) and then continues excessively on that track even when it is no longer warranted. This may be done by actively seeking only evidence to confirm that the hypothesis chosen is correct (the confirmation bias) or simply by ignoring competing and plausible hypotheses (cognitive tunneling).

Collectively, then, the joint cognitive processes of planning and problem solving (or troubleshooting), depending as they do on the interplay between working memory and long-term memory, reflect both the strengths and the weaknesses of human information processing. The output of each process is typically a decision: to undertake a particular course of action, to follow a plan, to choose a treatment based on the diagnosis, or to formulate a solution to the problem. The cognitive processes involved in such decision making are discussed extensively in Chapter 8, as are some of the important biases and heuristics in diagnosis discussed more briefly above.

5.5.3 Creativity

In general, creativity involves human problem solving that is relatively free from the confirmation bias, cognitive tunneling, and functional fixedness, each of which restricts the number of problem solutions we consider. For most theorists, creativity refers to the production of *effective novelty* (Cropley, 1999; Mayer, 1999). This is a process that involves thinking of a variety of previously untried solutions *and* judging their probable effectiveness. Finke et al. (1992) argue that *generating* novel cognitive structures involves retrieving, associating, synthesizing, and transforming information, while *evaluating* novel structures involves inferring, hypothesis testing, and context shifting, among other strategies. It is clear from this analysis that the cognitive load imposed by creative tasks can be immense and that working memory, including the storage systems and the central executive, will be taxed.

Novelty production may be particularly difficult to maintain for long periods of time for at least two reasons. First, the cognitive load imposed by creative problem solving, as we have described above, is high from the outset. Second, because novel stimuli often increase arousal levels, it is likely that the *production* of novelty will create a cycle of upward-spiraling arousal in the problem solver. This, in turn, will cause some degree of cognitive tunneling, making continued novelty production and evaluation difficult (Cropley, 1999). This may suggest that, unlike some other tasks, where higher levels of arousal may be desirable to maintain performance (e.g., long-duration search tasks for low-probability targets), creativity may be fostered by low initial levels of arousal.

The idea that novelty production may cause spiraling levels of arousal also provides one explanation for the often-discussed benefits of *incubation* for creative problem solving. Smith (1995) describes incubation in terms of the general finding that people are more likely to solve a problem after taking a break rather than working on a solution without interruption. In controlled trials, incubation effects are not invariably found (Nickerson, 1999); however, research continues to focus on the conditions under which incubation works. It is possible that a break from the act of novelty generation may serve to reduce arousal levels to more task-appropriate levels. Another explanation is that the probability of a new *problem representation* being put into action (e.g., the mental image or list of procedural steps being manipulated to generate solutions) is greater when a person disrupts his or her own processing. The person may simply be more likely to have forgotten components of a previous, ineffective representation upon returning to the task.

The importance of the cognitive representation of problems, and the different display formats that support these representations, has been demonstrated for a variety of problem-solving tasks (Davidson and Sternberg, 1998). Flexible scientific, information, and design visualization tools may prove to be particularly valuable for creative problem solving, because changing the orientation, color scheme, format, or level of focus will change the salience of different aspects of the problem. For example, when designers were asked to generate a design for a new lamp, Damle (2010) found that the use of design software that permitted monochromatic viewing of the otherwise multicolored designs helped the designers avoid fixating prematurely on design details. Presumably, this relatively simple change in the design software influenced designers' self-evaluations of their evolving designs, shifting their attention to global characteristics such as symmetry and balance. Developing software tools that reduce problems like functional fixedness, that instead encourage the perception of different aspects of the problem, are an important focus of current work on the design of *creativity support tools* (Schneiderman, 2009).

5.6 Metacognition and Change Blindness Blindness

We end our discussion of higher order cognitive processes by discussing a type of knowledge that may have a profound impact on the successful performance of any task, but especially on tasks involving problem solving, comprehension, and the maintenance of situation awareness. The term *metacognition* was introduced by Flavell (1979) to indicate a person's knowledge about his or her own cognitive processes and, further, the use of this information to regulate performance (Reder, 1996). The most active area of research on metacognition has been in education, where researchers have looked at how students' beliefs about their own information-processing capabilities influence learning strategies and ultimate academic success (Veenman et al., 2006; Bjork, 1999). However, the concept has important implications for the practice of human factors and ergonomics as well.

When describing metacognition, most researchers distinguish between *metacognitive knowledge* and *metacognitive control processes*. In general, metacognitive knowledge includes beliefs about one's own processing capacity, about potential strategies that enhance performance (or minimize capacity limits), and about when and why such strategies are appropriate (Schraw and Moshman, 1995). For example, an expert operator may come to the conclusion that it is more difficult to notice critical signals when they occur in a particular region of a visual display. Further, the operator may believe that he or she can compensate by oversampling that region but may also believe that oversampling will come at the cost of much greater mental effort. In contrast, Levine et al. (2000) have noted that most people are unaware of their strong tendencies toward change blindness, a metacognitive phenomenon referred to as "change blindness blindness." Clearly, such beliefs can influence the strategies an operator chooses. And it is important to realize that these beliefs may not be accurate and, further, that individuals, especially experts, may sometimes be unaware of the assumptions they are making (Chi et al., 1988).

Metacognitive control processes include planning, monitoring, and evaluating one's own performance (Schraw and Moshman, 1995). We might associate many of these processes with the functions of Baddeley's (2003) central executive in working memory. Planning includes determining the appropriate allocation of attention and time to different parts of a task as well as decisions about what aspects of performance to sacrifice if capacity limits create mandatory trade-offs (e.g., would a fast but inaccurate strategy be better than an accurate but slow one?). Monitoring involves keeping track of the quality of performance as a task progresses, for example, our ability to know whether or not we comprehend some written instructions well enough to act on them; or for the learner, whether we have studied enough on one lesson to have mastered the material and move on to the next. Finally, evaluation looks at the products of task performance and the control processes used to obtain them. This allows an assessment of how effectively we deployed our limited cognitive resources and may further elaborate our metacognitive knowledge in long-term memory.

Metacognitive knowledge and control processes are important for understanding human performance in a variety of domains. One important application is to determine how metacognitive knowledge may shape users' preferences for and use of specific interface and product designs. Users' choices may sometimes seem less than optimal based on existing performance data or predictions of formal performance models (Andre and Wickens, 1995). Cases in point are users' "intuitive" judgments of product usability. Payne (1995; see also Vu and Proctor, 2003), for example, explored users' judgments about the compatibility of different arrangements of multielement displays and controls. These judgments were not accurate predictors of actual performance using the different display–control arrangements, and the naïve judgments seemed to be based on the average "goodness" of the individual matches between each display and its associated control rather than on the match between the configuration of displays and controls. In short, the participants undervalued (or, perhaps, did not understand) the importance of configural properties on memory and performance.

Smallman and St. John (2005) propose that many users and designers alike fall prey to naïve realism, a tendency to prefer more realistic-looking displays, even when simpler formats would support better performance. In general, these authors attribute users' preferences to faulty metacognitive knowledge. For example, most individuals seem unaware of the inherent ambiguities of size and depth found in more realistic-looking 3D displays (see Section 4.4). They were also unaware of the relatively small portion of complex displays that they could process in a single glance, and they seemed not to consider the visual search costs that could result from increased display complexity.

Other examples of the impact of both metacogntive knowledge and control processes are found in drivers' overconfidence in their driving abilities in a variety of situations. For example, nighttime driving, as well as the use of devices such as cell phones, selectively degrades focal (central) vision which is critical for detecting hazards. Peripheral vision, which provides sufficient information for lane keeping, is relatively unimpaired by such factors. However, drivers may not appreciate the distinctive functions of each visual subsystem and may take satisfactory lane keeping as evidence that they have suffered no impairment from nighttime viewing conditions or in-vehicle distractions. This leads to dangerous overconfidence in their ability to detect and identify hazards, a task using a very different visual system and resources (see Section 7.2). In this case, metacognitive monitoring and performance evaluation are impaired, in part because the drivers have continuous feedback about lane keeping but only infrequent feedback about hazard detection. In addition, the driver's knowledge about their own perceptual systems may not lead them to suspect that one visual subsystem can be spared while another is degraded. Similar sorts of overconfidence may also be implicated when operators fail to use automation or decision support tools in circumstance where their own performance is deficient without these aids (e.g., McGuirl and Sarter, 2006).

When correctly diagnosed, metacognitive errors can be addressed in a variety of ways. Training is one approach, for example, providing information about the types of displays that best support different types of tasks (Milkman et al., 2009). Shen et al. (in press) found that the failure of users to select the appropriate perspective views to use when performing different emergency management tasks could be partially corrected with very simple verbal guidance about the best use of 2D versus 3D displays. Alternatively, poor strategy choices (or poor use of technology) might be addressed by providing better performance feedback to help users recalibrate their perceptions of their own skill levels, knowledge, and capabilities and to allow them to learn which performance strategies are most effective.

In this section we have discussed information-processing tasks that are time consuming, require extensive cognitive resources, and for which the "correct" response is poorly defined and multiple responses are possible, even desirable. We turn now to characteristics of actions that are typically selected rapidly, sometimes without much effort, and often without great uncertainty about their outcome.

6 ACTION SELECTION

6.1 Information and Uncertainty

In earlier sections we discussed different stages at which humans process information about the environment. When we turn to the stage of action selection and execution, a key concern addresses the *speed* with which information is processed from perception to action. How fast, for example, will the driver react to the unexpected roadway hazard or pedestrian or how rapidly will the help desk access computer information in response to a client's question. Borrowing from terminology in communications, we describe information-processing speed in terms of the *bandwidth*, the amount of information processed per unit time. In this regard, a unit of information is defined as a *bit*. One bit can be thought of as specifying between one of two possible alternatives, two bits as one of four alternatives, three bits as one of eight, or, in general, the number of bits (conveyed by an event) $= \log_2 N$, where N is the number of possible environmental events that could occur in the relevant task confronting the operator. In the following pages, after we describe a taxonomy of human actions, we will see how information influences the bandwidth of human processing.

The speed with which people perform a particular action depends jointly on the uncertainty associated with the outcome of that action and the skill of the operator in the task at hand. Rasmussen (1986; Rasmussen et al., 1995) has defined a behavior-level continuum that characterizes three levels of action selection and execution that is characterized by both uncertainty and skill. *Knowledge-based behavior* describes the action selection of the unskilled operator or of the skilled operator working in a highly complex environment facing a good deal of uncertainty. In the first case, we might consider a vehicle driver trying to figure out how to navigate through an unfamiliar city; in the second case, we consider the nuclear reactor operator trying to diagnose an apparent system failure. This is the sort of behavior discussed in Section 5.5.

Rule-based behavior typically characterizes actions that are selected more rapidly based on certain well-known rules. These rules map environmental characteristics (and task goals) to actions, and their outcomes are fairly predictable: "If the conditions exist, do X, then y, then z." The operator response in executing rule-based behavior is fairly rapid but is still "thought through" and may be carried out within the order of a few seconds. Working memory is required. Finally, *skilled-based behavior* is very rapid and nearly automatic in the sense that little working memory is required, performance of concurrent tasks is possible, and the action may be initiated within less than a second of the triggering event. Skill-based behavior, for example, characterizes movement of the fingers to a key to type a letter, the sequence of steering wheel turns used to back out of a familiar driveway or compensate for a wind gust, or the response of the pilot to an emergency ground proximity warning that says "pull up, pull up."

Human factors designers are quite interested in the system variables that affect the speed and accuracy of behavior of all three classes. Typically, those variables affecting knowledge-based behavior are discussed within the realm of problem solving and decision making (see Section 7 and Chapter 8). We discuss below the variables that influence rule- and skill-based behavior [see Wickens and Hollands (2000) for a more detailed discussion].

6.2 Complexity of Choice

Response times for either rule- or skill-based behavior become longer if there are more possible choices that could be made and therefore more information transmitted per choice (Hick, 1952; Hyman, 1953). The rule-based decision to go left or right at a Y fork in the road is simpler (i.e., 1 bit) and made more rapidly than at an intersection where there are four alternative paths (i.e., 2 bits). Menu selections take longer on a page where there are more menu options, and each stroke on a typewriter (26-letter options) takes longer to initiate than each depression of a Morse code key (two options). Indeed, the time to select an option is roughly proportional to the number of bits in the choice (Hick, 1952). As a guideline, designers should not give users more choices of action than are essential, particularly if time is critical. Long menus, with lots of rarely chosen options, may not be desirable. The consequences of offering many choices are not only longer response time but also an increased possibility that the wrong option will be chosen by mistake. More items typically lead to greater similarity between items and hence an invitation for confusion.

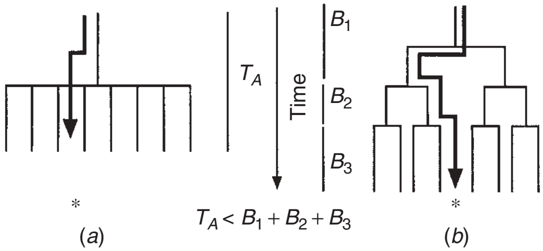

Figure 12 Decision complexity advantage: (*a*) total time required for three ''simple'' (low-complexity) choices; (*b*) time required for a single high-complexity choice. The total amount of information transmitted is the same in both cases.

The guidance for avoiding very complex choices presented above does not necessarily mean that very simple choices (e.g., 1 bit per choice) are necessarily best. Indeed, generally *an operator can transmit more total information per unit time with a few complex (information-rich) choices than several simple (information-poor) choices*. This conclusion, referred to as the *decision complexity advantage* (Wickens and Hollands, 2000), can be illustrated by two examples: First, an option provided by a single computer menu with eight alternatives (one complex decision) can be selected faster than an option provided by three consecutive selections from three two-item menus (three simple decisions; see Figure 12). Second, voice input, in which each possible word is a choice from a potentially large vocabulary (high complexity), can transmit more information per unit time than typing, with each letter indicating 1 of only 26 letters (less complex); and typing in turn can transmit more information per unit time than can Morse code. The general conclusion of the decision complexity advantage drawn from these examples and from other studies (Wickens and Hollands, 2000) points to the advantage of incorporating keys or output options that can select from a larger number of possible options, such as special service "macro" keys, keys that represent common words, or "chording" keyboard devices (Baber, 1997) that allow a single action selection (a chord depression using several fingers simultaneously) to select from one of several options.

In conclusion, it may seem that two contradictory messages were offered in the paragraphs above: (1) Keep choices simply, but (2) use a small number of complex choices. In resolving these two guidelines in design, it is best to think that the first guideline pertains to not providing a lot of *rarely* used options, particularly in time-stressed situations and when errors of choice can have high-risk consequences. The second guideline pertains to how to structure a choice among a large number of remaining and *plausible* options. A single choice among a larger list is often better than multiple sequential choices among smaller lists.

6.3 Probability and Expectancy

People respond more slowly (and are more likely to respond erroneously) to signals and events that they do not expect. Generally, such events are unexpected (or surprising) because they occur with a low probability in a particular context. This is consistent with our discussion of context effects on object identification in Section 4.2. Low-probability events, such as events with a greater number of alternatives, are also said to *convey more information*. The information in bits, conveyed by a single event that occurs with probability P, is $\log_2 2(1/P)$. As we noted above, greater information content requires more time for processing (Fitts and Peterson, 1964). For example, system failures usually occur rarely and as such are often responded to slowly or inappropriately. A similar status may characterize a driver's response to the unexpected appearance of a pedestrian on a freeway or to a traffic light that changes sooner than expected. The maximum expected response times to truly unexpected events provide important guidance to traffic safety engineers in determining issues related to speed limits and roadway characteristics (Evans, 1991; Summala, 2000). Often more serious than the slower response to the unexpected event is the potential failure to detect that event altogether (see Section 4.1). It is for this reason that designers ensure that annunciators of rare events are made salient and obtrusive or redundant (to the extent that the rare event is also one that is important for the operator's task; see Section 3).

6.4 Practice

Practice has two benefits to action selection. First, practice can move knowledge-based behavior into the domain of rule-based behavior and sometimes move rule-based actions into the domain of skill-based ones. The novice pilot may need to think about what action to take when a stall warning sounds, whereas the expert will respond automatically and instinctively. In this sense, practice increases both speed and accuracy. Second, practice will provide the operator with a sense of expectancy that is more closely calibrated with the actual probabilities and frequencies of events in the real world. Hence, frequent events will be responded to more rapidly by the expert; but ironically, expertise may lead to *less* speedy processing of the rare event than would be the case for the novice, for which the rare event is not perceived as unexpected.

6.5 Spatial Compatibility

The compatibility between a display and its associated control has two components that influence the speed and accuracy of the control response. One relates to the *location* of the control relative to the display, the second to how the display reflects (or commands) control *movement*. In its most general form, the *principle of location compatibility* dictates that the location of a control should correspond to the location of a display. There are several ways of describing this correspondence. Most directly, this correspondence is satisfied by the *principle of colocation*, which dictates that each display should be located adjacent to its appropriate control. But this is not always possible in systems when the displays themselves may be closely grouped (e.g., closely clustered on a display panel) or may not be reached easily by the operator because of other constraints (e.g., common visibility needed by a large group of operators on a group-viewed display or positioning the control for a display cursor on a head-mounted display).

When colocation cannot be maintained, the spatial compatibility *principle of congruence* takes over, which states that the spatial arrangement of a set of two or more displays should be congruent with the arrangement of their controls. One example of congruence is that left controls should be associated with left displays and right associated with right. In this regard, the distinction between "left" and "right" in designing for compatibility can be expressed either in relative terms (indicator A is to the left of indicator B) or in absolute terms relative to some prominent axis. This axis may be the body midline (i.e., distinguishing left hand from right hand) or it may be a prominent visual axis of symmetry in the system, such as that bisecting the cockpit on a twin-seat airplane design. When left–right congruence is violated such that a left display is matched to a right response, the operator may have a tendency to activate the incorrect control, particularly in times of stress (Fitts and Posner, 1967).

Sometimes an array of controls is to be associated with an array of displays (e.g., four-engine indicators). Here, congruence can be maintained (or violated) in several ways. Compatibility will best be maintained if the control and display arrays are parallel. It will be reduced if they are orthogonal (Figure 13; i.e., a vertical display array with a horizontal left–right or fore–aft control array). But even where there is orthogonality, compatibility can be improved by adhering to two guidelines: (1) The left end of a horizontal array should map to the near end of a fore–aft array (Figure 13*b*) and (2) the particular display (control) at the end of one array should map to the control (display) at the end of the other array to which it is closest (Andre and Wickens, 1990). It should be noted in closing, however, that the association of the top (or bottom) of a vertical array with the right (or left) level of a horizontal array is not a strong one. Therefore, ordered compatibility effects with orthogonal arrays will not be strong if one of those arrays is vertical (Chan and Hoffmann, 2010). Hence, some augmenting cue should be used to make sure that the association between the appropriate ends of the two arrays is clearly articulated (e.g., a common color code on both, or a painted line between them; Osborne and Ellingstad, 1987).

The movement aspect of SR compatibility may be defined as *intention–response–stimulus* (*IRS*) *compatibility*. This characterizes a situation in which the operator formulates an intention to do something (e.g., increase, activate, set, turn something on, adjust a variable). Given that intention, the operator makes a response or an adjustment. Given that response, some stimulus is (or should be) displayed as feedback from what has been done (Norman, 1988). There is a set of rules for this kind of mapping between an intention to respond, a response, and the display signal. The rules are based on the idea that people generally have a conception of how a quantity is ordered in space. As we noted in Section 4, when we think about something increasing, such as temperature, we think about a movement of a display that is upward (or from left to

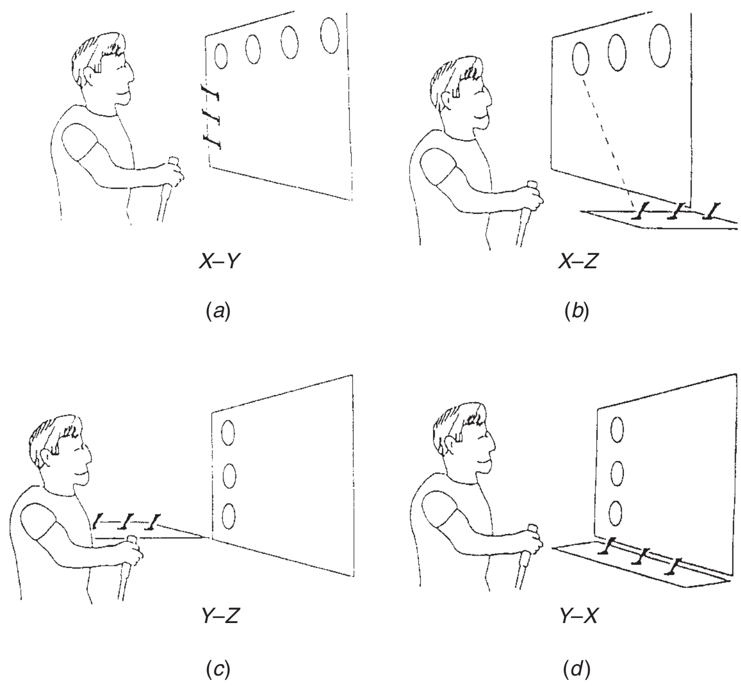

Figure 13 Different possible orthogonal display–control configurations

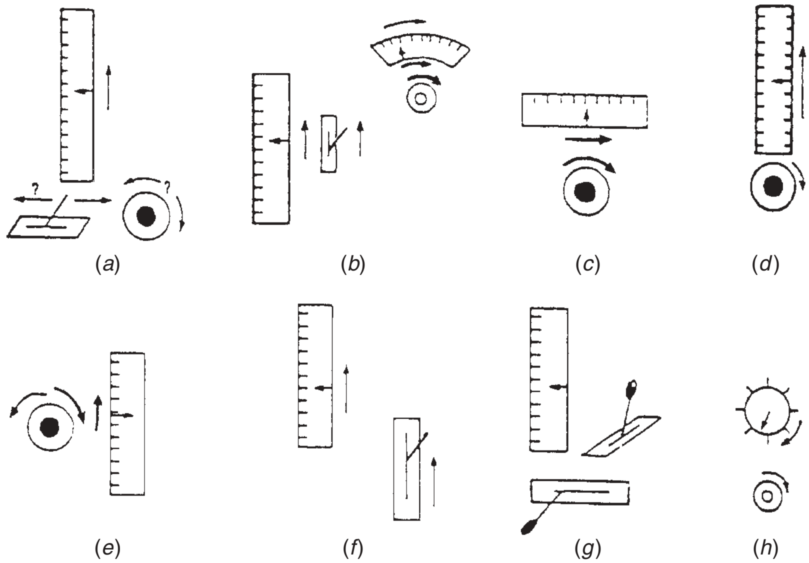

Figure 14 Examples of population stereotypes in control–display relations. (From Wickens, 1984.)

right, or clockwise). Both control and display movement should then be congruent in form and direction with this ordering. These guidelines are shown in Figure 14. Whenever one is dealing, for example, with a rotary control, people have certain expectations (a mental model) about how the movement of that control will be associated with the corresponding movement of a display. These expectancies may be defined as *stereotypes*, and there are three important stereotypes.

The first stereotype is the *clockwise increase stereotype*: A clockwise rotation of a control or display signals an increasing quantity (Figures 14*c* and *d*). The *proximity of movement stereotype* says that with any rotary control the arc of the rotating element that is closest to the moving display is assumed to move in the same direction as that display. In panel (*c*) of Figure 15, rotating the control clockwise is assumed to move the needle to the right, while rotating it counterclockwise is assumed to move the needle to the left (Chan and Hoffmann, 2010). It is as if the human's mental model is one that assumes that there is a mechanical linkage between the rotating object and the moving element, even though that mechanical linkage may not really be there.

Designers may sometimes develop control display relations that conform to one principle and violate another. Panel (*e*) shows a moving vertical-scale display with a rotating indicator. If the operator wants to increase the quantity, he or she rotates the dial clockwise. That will move the needle on the vertical scale up, thus violating the proximity-of-movement stereotype. The conflict may be resolved by putting the rotary control on the right side rather than the left side of a display. We have now created a display–control relationship that conforms to *both* the proximity-of-movement stereotype *and* the clockwise-to-increase stereotype.

The third stereotype of movement compatibility relates to *global congruence*. Just as with location compatibility, movement compatibility is preserved when controls and displays move in a congruent fashion: linear controls parallel to linear displays [(*f*), but not (*g*)] and rotary controls congruent with rotary displays [(*b*) and (*h*)]. Note, however, that (*h*) violates proximity of movement. When displays and controls move in orthogonal directions, as in (*g*), the movement relation between

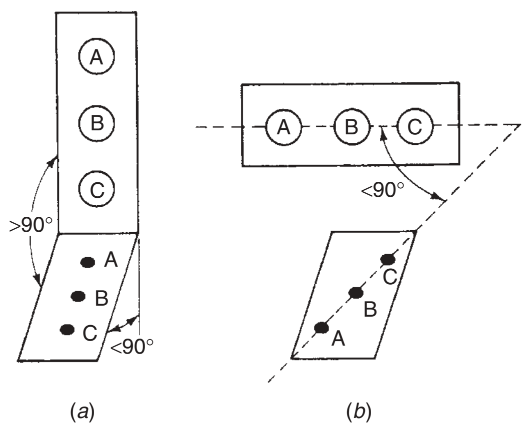

Figure 15 Solutions of location compatibility problems by using cant. (*a*) The control panel slopes downward slightly (an angle greater than 90°), so that control A is clearly above B and B is above C, just as they are in the display array. (*b*) The controls are slightly angled from left to right across the panel, creating a left–right ordering that is congruent with the display array. (From Wickens and Hollands, 2000.)

them is ambiguous. Such ambiguity, however, can often be reduced by placing a modest "cant" on either the control or display surface, so that some component of the movement axes are parallel, as shown in Figure 15.

6.6 Modality

Skilled responses in most human–machine systems are typically executed by either the hands or the voice. With increasingly sophisticated automated voice recognition systems, the latter option is becoming progressively more feasible. Although the particulars of voice control are addressed in more detail in Chapter 24, at least three characteristics of voice control are relevant here in the context of information processing:

1. Voice options allow more possible responses to be given in a shorter period of time without imposing added time-consuming finger movement components (i.e., keys), although this requires more sophisticated software in the voice recognition algorithms. Providing more options, enabling more complex decisions to be selected, is a positive benefit because it exploits the decision complexity advantage, as we saw in Section 6.2.
2. Voice options represent more compatible ways of transmitting symbolic or verbal information than are possible with spatially guided manual options (Wickens et al., 1984), including sequential keypresses. In contrast, voice responses make relatively poor candidates for transmitting continuous analog–spatial information, particularly in dynamic situations (e.g., tracking; Wickens et al., 1985), since spoken vocabulary is better equipped to generate categorical commands (e.g., "left," "right") than continuously modulated closed-loop commands (e.g., "a little more to the left").
3. Voice options are valuable in environments when the eyes, and in particular the hands, are otherwise engaged; but, conversely, voice options can be problematic in environments in which a large amount of other verbal activity is required, either by the user or by other people in the nearby workspace. The former causes competition for processing resources within the operator (see Section 7.2.3), while the latter creates the possibility of confusion on the part of the voice recognizer.

6.7 Response Discriminability

Whenever a set of manual responses are specified, any increases in the similarity between them (decreases in discriminability) will increase the likelihood of confusion. Thus, movement of the control stick to either one of two forward positions is a response choice that has greater opportunity for confusion than movement in either a forward *or* backward direction. Correspondingly, two buttons that look alike are more confusable (and hence error prone) than are two that are differently colored or shape coded. Although making controls physically distinct from each other may sometimes destroy a sense of aesthetics in design, such distinctions will generally lead to improved human reliability (Norman, 1988). Incidentally, increased similarity between voice control options (Section 6.6) will also produce the same increase in error likelihood, although here the mediating agent is the voice recognition agent (whether human or computer) rather than the human responder. Thus, the vocabulary selected for use in an application should be chosen with a mind to avoiding confusable-sounding articulations, such as "to" and "through."

6.8 Feedback

The quality of feedback provided by control manipulation (or action expression) is often critical to the speed of information transmission (Norman, 1988). Indeed, sometimes the problems of poor response discriminability discussed in Section 6.7 can be addressed and at least partially remedied by providing clear, salient, and immediate feedback as to which (of several confusable) response alternatives has been chosen. This feedback may be in the form of a visible light or an auditory or tactile "click" as the control reaches its appropriate destination.

It turns out, however, that salient feedback is not always necessary or even desirable. In particular, expert or highly skilled users rely far less on feedback than do novices (e.g., the skilled typist, when transcribing, rarely looks at the keyboard or the screen). Thus, if the feedback is salient (and hence intrusive), it may be distracting to the expert, even as it is valuable for the novice. This will be particularly true whenever the feedback is *delayed*, a quality that is especially disruptive for relatively continuous tasks such as data transcription or voice translation (Smith, 1962).

6.9 Continuous Control

Our discussion in Section 6.8 focused on the selection of *discrete* actions, such as a keypress or lever movement. Equally important are the *continuous* movements of some controls to reach targets in space. These movements may refer, for example, to the movement of the hand to a point on a touch screen, the movement of a cursor to an icon or word on a computer screen, or the movement of a pointer to a set point on a meter. Generically, then, we can speak of these skills involving movement of a *cursor* to a *target*.

To an even greater extent than the discrete movements discussed in Section 6.8, performance of these continuous-movement skills depends greatly on *visual feedback*, depicting the difference between the current cursor location and the desired target. Performance on control tasks in which a cursor is moved a certain distance into a target is well described by *Fitts's law* (Fitts, 1966; Jagacinski and Flach, 2003):

$$\text{Movement time} = a + b \log_2(2D/W)$$

where a and b are constants, D is the distance to the target, and W is the target width. This very robust law can accurately predict the movement of all sorts of devices, from microscopic pointers (Langolf et al., 1976) to cursor movements by mice (Card, 1981) to foot movement around a set of pedals (Drury, 1975) to the manipulation of endoscopic surgical instruments (Zheng et al., 2003). The basis of Fitts's law lies in the processing of visual feedback such that movement toward a target is maintained at a rate that is inversely proportional to the momentary distance of the target from the cursor (or other controlled object).

Just as Fitts's law nicely describes continuous movement toward a static target, it can also characterize movement of a cursor toward a *continuously* moving target, a process typically described as *tracking* (Wickens, 1986; Jagacinski and Flach, 2003). When operators engage in continuous tracking, however, whether keeping a car in the center of the highway, flying an airplane down a glide path, or moving one's viewpoint through a virtual environment via some control device, interest is more focused on minimizing the deviation from the target than on the time required to reach the target. Also, concern is less with the amplitude of the required movement than it is with other variables, such as the frequency with which corrections must be made (the *input signal bandwidth*), the complexity and lag of the *system dynamics* mediating between hand movement and cursor or output movement, and the manner in which feedback is displayed. These issues extend well beyond the scope of the current chapter and are covered in more depth in Chapter 5. We also note that compatibility effects in continuous control are also addressed in Section 4.5.

6.10 Errors

The previous discussion has focused primarily on the *time* required to process and respond to various items of information. Yet in many systems the occurrence of *errors* is more critical than the occurrence of delays in processing. That is, the loss of information, rather than its transmission delay, is the factor of greatest concern. Although errors are treated extensively in Chapter 27, we wish here to highlight the manner in which different classes of errors can be categorized in the context of the flow of information as depicted in Figure 1*a* (Norman, 1981; Reason, 1990, 1997, 2008).

First, *mistakes* represent errors of the earlier stages of information processing, in which incorrect action is carried out as a result of a failure to *understand* the nature of a situation (i.e., a failure of stage 2 or stage 3 situation awareness, as discussed in Section 5.2). This may result from a breakdown in perception or working memory or from insufficient knowledge to interpret the available cues (i.e., *knowledge-based errors*). Second, while a situation may be diagnosed and understood correctly, *rule-based errors* may result from a failure to apply the correct rules appropriately for selection of a response (Reason, 1990). Third, errors may result from *slips* of action, when the correct response is intended but an incorrect action is actually released (i.e., an unintended response "slips" out of the hands or mouth) (Norman, 1981). Slips of this sort are typically the result of poor human factors design, such as incompatible control–display relationships (see Section 6.5), confusable displays (Section 1) or controls (Section 6.7), coupled with an operator who is well skilled and performing a task in a highly automated mode, thereby not carefully monitoring his or her own action selections.

A particular version of the slip is called the *mode error*, often observed in multimodal systems, where the operator forgets that the system is in one mode, thinking it is in another one, and executes a series of actions which have a very different effect on the system than intended. A trivial case is when a typist, without using visual feedback, is unaware that the keyboard is in the caps mode. In safety-critical systems, however, mode errors can have major consequences, as, for example, when a speed control can be set to a digital value which controls kilometers per hour or meters per second, depending on the mode setting. Clearly, such multimode systems must be accompanied by salient feedback of the existing mode.

Errors can also be attributed directly to a breakdown of *memory*. As noted in Section 2, working memory breakdowns may lead to forgetting or confusion of material, whereas *errors of prospective memory* may lead operators to forget to perform some action that was previously intended (Loukopopolous et al., 2009). Often described as *errors of omission*, these are typified by leaving the last copied paper on the glass of a photocopier or failing to tighten the bolts after completing a maintenance task (Reason, 1997).

It is usually the case that the conditions that are associated with slower processing are those that also produce more errors, and hence design remediation based on measures of processing speed will be productive in improving overall system accuracy. However, in certain circumstances, a strategic adjustment in how an operator performs a task will lead to an inverse relationship between speed and accuracy: the *speed–accuracy tradeoff*. In this case, a "set" to respond rapidly will lead to more rather than fewer errors (Drury, 1994). An example here would be that of the effects of time stress in emergencies, which may lead to hasty but error-prone actions in the processing of information.

7 MULTIPLE-TASK PERFORMANCE

Many task environments require operators to process information from more than one source and to perform more than one task at a time (Damos, 1991; Loukopopolous et al., 2009; Wickens and McCarley, 2008; Salvucci and Taatgen, 2011; Regan et al., 2009). Such environments are as diverse as that confronting the secretary conversing with the supervisor while typing, the maintenance technician who performs and observes diagnostic tests while keeping active hypotheses about possible faults rehearsed in working memory, the vehicle driver placing a cell phone call while searching for a road sign and steering (Regan et al., 2009; Collet et al., 2010), or the basketball point guard dribbling, while scanning the defense, and looking for the cutting forward.

In such multiple-task environments requiring divided attention, we may distinguish between three qualitatively different *modes* of multiple-task behavior: *perfect parallel processing*, in which two (or more) tasks are performed concurrently as well as either is performed alone; *degraded concurrent processing*, in which both tasks are performed concurrently but one or both suffers relative to its single task level; and *strict serial processing*, during which only one task is performed at a time. Each of these modes is observed under different circumstances and has somewhat different implications for design.

7.1 Serial Processing and Interruption Management

The concerns of serial processing result when performance of one task or the other is delayed undesirably because of sequential constraints. Such a delay might characterize the behavior of a pilot who fails to check the aircraft altimeter sufficiently often because he is engaged in other visual tasks, leading to dangerous "altitude busts" (Raby and Wickens, 1994; Dismukes, 2001). Typically, the interests of human factors in sequential task performance are in modeling the decision process whereby the operator chooses to perform one task (and, by necessity, neglects another) at any given moment in time. This choice process is often modeled by *queuing theory* (Kleinman and Pattipati, 1991; Meyer and Kieras, 1997; Liu et al., 2006) or variants thereof (Moray, 1986; Wickens et al., 2003), which specify when a task should be sampled (performed) as a function of that task's importance (cost of not performing it) and the frequency with which it should be carried out. When evaluated against these optimal benchmarks, human performance appears to be reasonably optimal subject to the constraints of working memory.

However, reasonably optimal is not the same thing as perfectly optimal, and others have focused interest on the occasional breakdowns in optimality that do occur. Thus, a different approach to human multiple-task performance is to focus on the accidents and incidents that have apparently resulted from failures of effective task management (Raby and Wickens, 1994; Chou et al., 1996; Loukopopolous et al., 2009; Schutte and Trujillo, 1996; Orasanu and Fischer, 1997; Wickens, 2003b); that is, what causes people to neglect a task.

Here the answers based on empirical research are not entirely clear, although two prominent factors do appear to emerge. First, visible, and in particular audible, reminders to do a task increase the likelihood that that task will be done, compared to circumstances in which task initiation must be based on prospective memory alone (Norman, 1988; Dismukes and Nowinski, 2007). The vulnerability of such memory highlights the value of checklists as visual reminders for people to carry out certain actions at certain times (Degani and Wiener, 1993; Herrmann et al., 1999; Wickens, 2003b). Second, heavy involvement (high workload) with one task may lead an operator to neglect a second task and perhaps fail to return to an activity at a time when that return should be critical. Such high workload can amplify the negative effects of change blindness discussed in Section 3.1, given that such environmental changes often announce a task to which attention should be redirected. This deficiency may be addressed through task or workload management training programs (Loukopopolous et al., 2009).

Of course, task switching is a two-way street. The desirable properties of having the waiting task call attention to itself may also have the undesirable properties of interrupting an ongoing task, to the detriment of the latter (McFarlane and Latorella, 2002). Recently, study has focused on the concept of *interruption management.* This domain of interruption management embodies the research on situations which represent an operator performing an ongoing task (OT), being interrupted by an interrupting task (IT) and then returning to the OT (Trafton and Monk, 2007; Iani and Wickens, 2007; Latorella, 1996). This sequence (OT–IT–OT) can be thought of as a "unit of interruption." If the cycle is repeated many times, it represents the more general paradigm of task switching (Monsell, 2003), or task interleaving (Wickens and McCarley, 2008). Because interruptions and task switching seem to be an inevitable part of the modern workplace (Gonzales and Mark, 2004; Wolf et al., 2006), we ask if there are any general rules, tendencies, or factors that make interruption management more or less fluid.

One approach to the study of IM has focused on the first attention switch, from the OT → IT, and the extent to which *preemption* of the OT by the IT is optimal or not. IT modality certainly makes a difference here, as auditory and tactile alerts are more preferred than visual, but the two nonvisual modalities can sometimes be sufficiently intrusive that they can lead to abandoning the OT at nonoptimal times; auditory interruptions, like a phone call, are often hard to ignore. A promising approach is one in which the IT event can signal its own degree of importance, so that the performer can establish whether a switch need be immediate (Ho et al., 2004) before the OT is abandoned.

A second approach, related to *cognitive tunneling*, has been to focus on properties of an OT that will prevent the switch when in fact it should have occurred. This is the study of "engagement." For example, studies of cell phone use in cars suggest that the more "engaging" is the conversational task, the less likely is the driver (or simulated driver) to switch attention from the task to address an unexpected event in the driving task (Horrey and Wickens, 2006; Collet et al., 2010). Failure or fault management in complex systems (the OT) has also been associated with such tunneling, where attention is not switched to deal with other high-priority events that may occur as the operator is trying to deal with the fault (Dismukes and Nowinski, 2007). Aviation data also suggest that compelling immersive 3D displays can lead to this sort of attentional tunneling in the OT, causing a failure to switch to unexpected IT events (Wickens and Alexander, 2009; Wickens et al., 2009a).

A third approach to interruption management is to examine the resumption of the OT after an interruption. Much of this work is based on a theory of "memory for goals" or "goal activation" (Trafton and Monk, 2007), in which the critical determinant of resumption is how well the goals of the OT are mentally preserved during the IT period. For example, actions taken prior to IT switching (i.e., active "placekeeping" or "bookmarking," or rehearsal) can serve to maintain the goal in a more active state at the time of the second (IT → OT) switch and hence increase the fluency of restarting the OT (McDaniel and Einstein, 2007). The state of the OT at the time of the interruption can also be briefly rehearsed (Trafton et al, 2003). In a corresponding fashion, strategically postponing switch 1 until a subgoal in the OT has been completed ("let me just finish this paragraph") will better enable starting the OT where it was left off, rather than having to "start from scratch." A closely related factor is the modality of the OT. When this involves processing speech, because speech is transient and vulnerable and must be rehearsed, there is more of a tendency to delay the abandonment of the OT when it is in the vocal, rather than the text modality, because in the former case an instant switch may lead to forgetting what was just said and require a request for a repeat upon return to the OT; in the latter, with print, one can simply go back and read the still-present text (Latorella, 1996).

Designers of human–computer interfaces are considerintg ways in which intelligent automation can postpone interruptions of a user's ongoing task until the inference is made that a subgoal has been completed (Bailey and Konstan, 2006).

We also note that similar strategic factors in interruption management influence switching in dynamic control tasks; people do (or at least should) schedule switches when the system is in a more stable state. For example, in driving, it is more optimal to look downward to a secondary task, when the car is centered in the lane and heading straight, than when the car may be veering toward one side or the other. Switching in stable states during dynamic control is analogous to switching cognitive states after subgoal completion.

In closing, it should be noted that some concurrent task performance may be invoked during interruption management to the extent that the operator may be attempting to rehearse the goals or status of the OT while addressing the IT. We now turn to this issue of concurrent task performance.

7.2 Concurrent Processing

In contrast to sequential processing, an understanding of concurrent processing, whether in degraded mode or perfect parallel mode, depends on somewhat different mechanisms. These mechanisms are as closely related to the structure of the information-processing sequences within the tasks themselves as they are to the operator's knowledge of task importance and priority (although there are interactions between these two influences; Gopher, 1992). Here human factors interest is in the task features that can enable any sort of concurrent processing to emerge from serial processing and that can enable that concurrent processing to be perfect rather than degraded. Four characteristics appear to influence this degree of success: task similarity, task demand, and task structure and resource allocation (Wickens, 2002, 2007; Wickens and Hollands, 2000), although how these influences are exerted is somewhat complex.

7.2.1 Task Similarity

A high degree of similarity between two tasks may induce confusion, just as similarity between perceptual signals will cause confusion (Section 3.3), high similarity between items held in working memory will increase the degree of interference between them (Section 5.1), or high similarity between two response devices will increase the possibility of confusion of actions (Section 6.7). In the context of interruption management, high similarity between the OT and the IT will degrade performance, because the remembered status of the OT will get confused with material from the IT (Dismukes and Nowinski, 2007; Cellier and Eyrolle, 1992).

In contrast to similarity of material, making the *rules* governing two tasks more similar may allow the tasks to be better integrated, fostering *more* effective concurrent processing. This may involve using similar control dynamics on two axes of a tracking task (Chernikoff and LeMay, 1963; Fracker and Wickens, 1989) or using similar rules to map stimuli (events) to responses (actions) (Duncan, 1979). Rule similarity also facilitates the ability of an operator to *switch* attention between two tasks in sequential fashion when in the serial mode of processing. That is, it is easier to keep doing alternative versions of the same task than it is to switch between different tasks, as if there is some "overhead" penalty for switching rules (Rogers and Monsell, 1995).

7.2.2 Task Demand

Easier tasks are more likely to be performed concurrently (and perfectly) than are more difficult or demanding tasks, an intuitive effect well documented in the study of cell phone interference with driving (Collet et al., 2010). We argue that easier tasks are generally more automated and consume less mental effort or resources than do more difficult ones (see Chapter 9). Such automaticity can often be achieved by extensive practice on what are called *consistently mapped tasks* (Fisk et al., 1987). These are tasks in which in each encounter by the learner, certain properties of the relation between the displayed elements, cognitive operations, and responses remain constant. These mimic many properties of skill- and rule-based tasks, as described in Section 6.5. Such consistent mapping will lead to not only more rapid performance but also performance that is relatively attention free and hence will allow other tasks to be time shared successfully.

7.2.3 Task Structure

Certain structural differences between two time-shared tasks increase the efficiency of their concurrent processing, as if the two tasks demand entirely (or partially) separated resources within the human processing system, such that it is easier to distribute tasks across *multiple resources* than to focus them within a single resource (Wickens, 1991, 2002; Wickens et al., 2003). These resources appear to be defined by *processing code* (verbal or linguistic versus spatial), *processing stage* (perceptual–cognitive operations versus response operations), *perceptual modality* (auditory versus visual), and *visual subsystems* (focal vision, required for object recognition, versus ambient vision, required for orientation and locomotion; Previc, 1998).

To briefly illustrate these dichotomies of resources, it is because of the separate spatial and verbal code resources that spatially guided manual responses may be more effective than vocal responses when operators must also rehearse verbal material, but vocal responses will be more effective than spatially guided manual ones when the operator must concurrently perform another spatial task, such as tracking (e.g., the disruption of driving caused by cell phone dialing, Collet et al., 2010). As another example of code interference, we saw in Section 5.4 that the spatial cognitive processes involved in navigation and vehicle control are better time shared with the verbal input of a memorized verbal route list than the spatial input of a memorized map. It is because of the separate stage-defined resources that we are often able effectively to time share responding operations (e.g., talking) with perceptual ones (e.g., scanning). It is because of the separate perceptual resources that designers have chosen to offload the heavy visual processing load of pilots and vehicle drivers with some information presented on auditory channels (Wickens et al., 2003). Finally, it is because of the separate visual channels that we can effectively keep a car centered in the lane (using ambient vision) while searching for and reading road signs (a task requiring focal vision).

7.2.4 Resource Allocation

Multiple resource demand (the converse of automaticity) and resource type can predict the total amount of interference between two tasks (Wickens, 2005), but the two constructs together say nothing about the extent to which one task or the other suffers the greater decrement or bears the brunt of that interference. This relative decrement is predicted by *task priority* or the *resource allocation policy* between the two, the third element of multiple resource model (Wickens, 2007). Such policy will be at least partially influenced by task importance, but other factors may come into play here, such as the difficulty of the task (greater emphasis is given to the harder task) or the task's intrinsic interest or *engagement* value, the latter describing the occasional interference of cell phone conversation with safe driving, despite the driving tasks' generally greater importance.

8 CONCLUSIONS

In conclusion, the systems with which people must interact vary vastly in their complexity, from the simple graph or tool to things like nuclear reactors or the physiology of a patient under anesthesia. As a consequence, they vary drastically in terms of the type and degree of demands imposed on the varying information-processing components we have discussed in this chapter. In some cases, systems will impose demands on components that are quite vulnerable: working memory, predictive capabilities, and divided attention, for example. At other times they may impose on human capabilities that are a source of great strength, particularly if these sources rely on the vast store of information that we retain in long-term memory, information that assists us in pattern recognition, top-down processing, chunking, and developing plans and scripts on the basis of past experience are examples. The importance of practice and training in the development of this knowledge base cannot be overestimated.

In addition to facilitating the performance of experts in many ways, long-term memory has a second implication for the practice of human factors. This is that predictions of human performance in many systems can be based only partially on an understanding of the generic information-processing components described in this chapter. An equal and sometimes greater partner in this prediction is extensive *domain knowledge* regarding the particular system with which the human is interacting. As several of the chapters in this handbook address, the best prediction of human performance must be based on the intricate interaction between the information-processing components discussed here, the domain knowledge employed by the human operator, and the physical environment within and tools with which the operator works. The reader will find all of these issues covered from multiple perspectives in subsequent chapters of the handbook.

REFERENCES

Adams, M. J., Tenney, Y. J., and Pew, R. W. (1991), "Strategic Workload and the Cognitive Management of Advanced Multi-Task Systems," SOAR CSERIAC 91-6, Crew System Ergonomics Information Analysis Center, Wright-Patterson AFB, OH.

Adams, M. J., Tenney, Y. J., and Pew, R. W. (1995), "Situation Awareness and the Cognitive Management of Complex Systems," *Human Factors*, Vol. 37, No. 1, pp. 85–104.

Adamson, R. E. (1952), "Functional Fixedness as Related to Problem Solving: A Repetition of Three Experiments," *Journal of Experimental Psychology*, Vol. 44, pp. 288–291.

Allpress, J. A., and Leland, L. S. (2010), "Reducing Traffic Speed within Roadwork Sites Using Obtrusive Perceptual Countermeasures," *Accident Analysis and Prevention*, Vol. 42, pp. 377–383.

Andre, A. D., and Wickens, C. D. (1990), "Display Control Compatibility in the Cockpit: Guidelines for Display Layout Analysis," University of Illinois Institute of Aviation Technical Report ARL-90-12/NASA-A3I-90-1, Aviation Research Laboratory, Savoy, IL.

Andre, A. D., and Wickens, C. D. (1995), "When Users Want What's NotBest for Them," *Ergonomics in Design*, Vol. 3, No. 4, pp. 10–14.

Aretz, A. J. (1991), "The Design of Electronic Map Displays," *Human Factors*, Vol. 33, No. 1, pp. 85–101.

Ariely, D. (2001), "Seeing Sets: Representation by Statistical Properties," *Psychological Science*, Vol. 12, pp. 157–162.

Atkinson, R. C., and Shiffrin, R. M. (1971), "The Control of Short-Term Memory," *Scientific American*, Vol. 225, pp. 82–90.

Awh, E., Jonides, J., and Reuter-Lorenz, P. A. (1998), "Rehearsal in Spatial Working Memory," *Journal of Experimental Psychology: Human Perception and Performance*, Vol. 24, pp. 780–790.

Baber, C. (1997), *Beyond the Desktop*, Academic, San Diego, CA.

Baddeley, A. (2000), "The Episodic Buffer: ANew Component of Working Memory?" *Trends in Cognitive Sciences*, Vol. 4, No. 11, pp. 417–423.

Baddeley, A. (2003), "Working Memory: Looking Back and Looking Forward," *Nature Reviews Neuroscience*, Vol. 4, pp. 829–839.

Baddeley, A. D., and Hitch, J. G. (1974), in *The Psychology of Learning and Motivation*, Vol. 8, G. A. Bower, Ed., Academic, New York, pp. 47–89.

Bailey, B. P., and Konstan, J. A. (2006), "On the Need for Attention-Aware Systems: Measuring Effects of Interruption on Task Performance, Error Rate, and Affective State," *Computers in Human Behavior*, Vol. 23, pp. 685–708.

Baker, C. H. (1961), "Maintaining the Level of Vigilance by Means of Knowledge of Results About a Secondary Vigilance Task," *Ergonomics*, Vol. 4, pp. 311–316.

Ballard, D. H., Hayhoe, M. M., and Pelz, J. B. (1995), "Memory Representation in Natural Tasks," *Journal of Cognitive Neuroscience*, Vol. 7, No. 1, pp. 66–86.

Banbury, S. P., and Treselian, S. (2004), *Cognitive Approaches to Situation Awareness*, Ashgate, Brookfield, VT.

Banbury, S. P., Macken, W. J., Tremblay, S., and Jones, D. M. (2001), "Auditory Distraction and Short-Term Memory: Phenomena and Practical Implications," *Human Factors*, Vol. 43, pp. 12–29.

Barnett, B. J, and Wickens, C. D. (1988), "Display Proximity in Multicue Information Integration: The Benefit of Boxes," *Human Factors*, Vol. 30, pp. 15–24.

Bellenkes, A. H., Wickens, C. D., and Kramer, A. F. (1997), "Visual Scanning and Pilot Expertise: The Role of Attentional Flexibility and Mental Model Development," *Aviation, Space, and Environmental Medicine*, Vol. 68, No. 7, pp. 569–579.

Bennett, K. B., and Flach, J. M. (1992), "Graphical Displays: Implications for Divided Attention, Focused Attention, and Problem Solving," *Human Factors*, Vol. 34, pp. 513–533.

Bennett, K. B., and Fritz, H. I. (2005), "Objects and Mappings: Incompatible Principles of Display Design" *Human Factors*, Vol. 47, No. 1, pp. 131–137.

Bennett, K. B., Toms, M. L., and Woods, D. D. (1993), "Emergent Features and Graphical Elements: Designing More Effective Configural Displays," *Human Factors*, Vol. 35, No. 1, pp. 71–98.

Beringer, D. B., and Chrisman, S. E. (1991), "Peripheral Polar-Graphic Displays for Signal/Failure Detection," *International Journal of Aviation Psychology*, Vol. 1, pp. 133–148.

Biederman, I. (1987). "Recognition-by-components: A theory of human image understanding." *Psychological Review*, *94*(2), 115–147.

Biederman, I., Mezzanotte, R. J., Rabinowitz, J. C., Francolin, C. M., and Plude, D. (1981), "Detecting the Unexpected in Photo Interpretation," *Human Factors*, Vol. 23, pp. 153–163.

Bizantz, A., and Roth, E. (2007), "Analysis of Cognitive Work," in *Reviews of Human Factors & Ergonomics*, Vol. 3, D. Boehm-David, Ed., Human Factors Society, Santa Monica, CA.

Bjork, R. A. (1999), "Assessing Our Own Competence: Heuristics and Illusions", in *Attention & Performance*, Vol. 17, D. Gopher and A. Koriat, Eds., MIT Press, Cambridge, MA.

Blake, R., and Sekuler, R. (2006), *Perception*, 5th ed., McGraw-Hill, Boston.

Bransford, J. D., and Johnson, M. K. (1972), "Contextual Prerequisites for Understanding: Some Investigations of Comprehension and Recall," *Journal of Verbal Learning and Verbal Behavior*, Vol. 11, pp. 717–726.

Braunstein, M. L., Andersen, G. J., Rouse, M. W., and Tittle, J. S. (1986), "Recovering Viewer Centered Depth from Disparity, Occlusion and Velocity Gradients," *Perception and Psychophysics*, Vol. 40, No. 4, pp. 216–224.

Breznitz, S. (1983), *Cry Wolf: The Psychology of False Alarms*, Lawrence Erlbaum Associates, Mahwah, NJ.

Broadbent, D. (1958), *Perception and Communications*, Permagon, New York.

Broadbent, D. (1972), *Decision and Stress*, Academic, New York.

Broadbent, D. E. (1982), "Task Combination and Selective Intake of Information," *Acta Psychologica*, Vol. 50, pp. 253–290.

Brown, J. (1959), "Some Tests of the Decay Theory of Immediate Memory," *Quarterly Journal of Experimental Psychology*, Vol. 10, pp. 12–21.

Buchner, A., Brandt, M., Bell, R., and Weise, J. (2006), "Car Backlight Position and Fog Density Bias Observer-Car Distance Estimates and Time-to-Collision Judgments," *Human Factors*, Vol. 48, pp. 300–317.

Burns, C. (2000), "Putting It All Together: Improving Integration in Ecological Displays," *Human Factors*, Vol. 42, pp. 226–241.

Burns, C. M., Bisantz, A. M., and Roth, E. M. (2004), "Lessons from a Comparison of Work Domain Models," *Human Factors*, Vol. 46, pp. 711–727.

Buttigieg, M. A., and Sanderson, P. M. (1991), "Emergent Features in Visual Display Design for Two Types of Failure Detection Tasks," *Human Factors*, Vol. 33, pp. 631–651.

Card, S. K. (1981), "The Model Human Processor: A Model for Making Engineering Calculations of Human Performance," in *Proceedings of the 25th Annual Meeting of the Human Factors Society*, R. Sugarman, Ed., Human Factors Society, Santa Monica, CA.

Carpenter, P. A., and Just, M. A. (1975), "Sentence Comprehension: A Psycholinguistic Processing Model of Verification," *Psychological Review*, Vol. 82, No. 1, pp. 45–73.

Carswell, C. M. (1992), "Reading Graphs: Interactions of Processing Requirements and Stimulus Structure," in *Precepts, Concepts, and Categories*, B. Burns, Ed., Elsevier Science, Amsterdam, pp. 605–647.

Carswell, C. M., and Wickens, C. D. (1987), "Information Integration and the Object Display: An Interaction of Task Demands and Display Superiority," *Ergonomics*, Vol. 30, pp. 511–527.

Carswell, C. M., and Wickens, C. D. (1990), "The Perceptual Interaction of Graphical Attributes: Configurality, Stimulus Homogeneity, and Object Integration," *Perception and Psychophysics*, Vol. 47, pp. 157–168.

Carswell, C. M., and Wickens, C. D. (1996), "Mixing and Matching Lower-Level Codes for Object Displays: Evidence for Two Sources of Proximity Compatibility," *Human Factors*, Vol. 38, pp. 61–72.

Cellier, J., and Eyrolle, H. (1992), "Interference between Switched Tasks," *Ergonomics*, Vol. 35, No. 1, pp. 25–36

Chan, A., and Hofmann, E. (2010), "2010" *Ergonomics*, Vol. 53, pp. 1403–1419
Chernikoff, R., and LeMay, M. (1963), "Effect of Various Display-Control Configurations on Tracking with Identical and Different Coordinate Dynamics," *Journal of Experimental Psychology*, Vol. 6, pp. 95–99.
Chi, M. T. H., Glaser, R., and Farr, M. J., Eds. (1988), *The Nature of Expertise*, Erlbaum, Hillsdale, NJ.
Chong, S. C., and Treisman, A. (2005), "Statistical Processing: Computing the Average Size in Perceptual Groups," *Vision Research*, Vol. 45, pp. 891–900.
Chou, C., Madhavan, D., and Funk, K. (1996), "Studies of Cockpit Task Management Errors," *International Journal of Aviation Psychology*, Vol. 6, No. 4, pp. 307–320.
Clark, H. H., and Chase, W. G. (1972), "On the Process of Comparing Sentences Against Pictures," *Cognitive Psychology*, Vol. 3, pp. 472–517.
Cleveland, W. S. (1985), *The Elements of Graphing Data*, Wadsworth, Monterey, CA.
Cleveland, W. S., and McGill, R. (1984), "Graphical Perception: Theory, Experimentation, and Application to the Development of Graphic Methods," *Journal of the American Statistical Association*, Vol. 70, pp. 531–554.
Cleveland, W. S., and McGill, R. (1985), "Graphical Perception and Graphical Methods for Analyzing Scientific Data," *Science*, Vol. 229, pp. 828–833.
Cohen, H. H. (2003), "Why Do We Bump into Things While Walking? Revisited," *Ergonomicsin Design*, Vo. 11, No. 4, pp. 12–15.
Collet, C., Guillot, A., and Petit, C. (2010), "Phoning While Driving II: A Review of Driving Condition Influence," *Ergonomics*, Vol. 53, pp. 602–616.
Cropley, A. J. (1999), "Creativity and Cognition: Producing Effective Novelty," *Roeper Review*, Vol. 21, pp. 253–260.
Cutting, J. E., and Vishton, P. M. (1995), "Perceiving Layout and Knowing Distances: The Integration, Relative Potency, and Contextual Use of Different Information About Depth," in *Perception of Space and Motion*, W. Epstein and S. Rogers, Eds., Academic, San Diego, CA.
Damle, A. (2010), "Using Monochromatic Design Views to Avoid a Premature Fixation on Design Solutions," *Human Factors*, Vol. 52, No. 1, pp. 28–40.
Damos, D., Ed. (1991), *Multiple Task Performance*, Taylor & Francis, London.
Davidson, J. E., and Sternberg, R. J. (1998), "Smart Problem-Solving: How Metacognition Helps," in *Metacognition in Educational Theory and Practice*, D. J. Hacker, J. Dunlosky, and A. C. Graesser, Eds., Lawrence Erlbaum Associates, Mahwah, NJ, pp. 47–65.
Degani, A., and Wiener, E. L. (1993), "Cockpit Checklists: Concepts, Design, and Use," *Human Factors*, Vol. 35, No. 4, pp. 345–360.
DeLucia, P. R., Mather, R. D., Griswold, J. A., and Mitra, S. (2006), "Toward the Improvement of Image-Guided Interventions for Minimally Invasive Surgery: Three Factors That Affect Performance," *Human Factors*, Vol. 48, No. 1, pp. 23–38.
Denton, G. G. (1980), "The Influence of Visual Pattern on Perceived Speed," *Perception*, Vol. 9, pp. 393–402.
DeSoto, C. B., London, M., and Handel, S. (1965), "Social Reasoning and Spatial Paralogic," *Journal of Personal and Social Psychology*, Vol. 2, pp. 513–521.
Dismukes, K. (2001), "The Challenge of Managing Interruptions, Distractions, and Deferred Tasks," in *Proceedings of the 11th International Symposium on Aviation Psychology*, Ohio State University, Columbus, OH.
Dismukes, K., and Nowinski, J. (2007). "Prospective Memory, Concurrent Task Management and Pilot Error," in, *Attention: From Theory to Practice*, A. Kramer, D. Wiegmann, and A. Kirlik, Eds., Oxford University Press, Oxford.
Dixon, S., Wickens, C. D., and McCarley, J. M. (2007), "On the Independence of Reliance and Compliance: Are False Alarms Worse Than Misses," *Human Factors*, Vol. 49, pp. 564–572.
Drury, C. (1975), "Application to Fitts' Law to Foot Pedal Design," *Human Factors*, Vol. 17, pp. 368–373.
Drury, C. (1994), "The Speed-Accuracy Tradeoff in Industry," *Ergonomics*, Vol. 37, pp. 747–763.
Drury, C. G., and Addison, S. L. (1973), "An Industrial Study of the Effects of Feedback and Fault Density on Inspection Performance," *Ergonomics*, Vol. 16, pp. 159–169.
Duncan, J. (1979), "Divided Attention: The Whole Is More Than the Sum of Its Parts," *Journal of Experimental Psychology: Human Perception and Performance*, Vol. 5, pp. 216–228.
Duncan, J. (1984), "Selective Attention and the Organization of Visual Information", *Journal of Experimental Psychology: General*, Vol. 119, pp. 501–517.
Durso, F., Rawson, K., and Girotto, S. (2007), "Comprehension and Situation Awareness," in *Handbook of Applied Cognition*, F. Durso, Ed., Wiley, Chichester.
Durso, F. T., Truitt, T. R., Hackworth, C., Crutchfield, J., and Manning, C. A. (1998), "En Route Operational Errors and Situation Awareness," *International Journal of Aviation Psychology*, Vol. 8, pp. 177–194.
Eberts, R. E., and MacMillan, A. G. (1985), "Misperception of Small Cars," in *Trends in Ergonomics/Human Factor*, Vol. 2, R. E. Eberts and C. G. Eberts, Eds., Elsevier Science, Amsterdam, pp. 33–39.
Egeth, H. E., and Yantis, S. (1997), "Visual Attention: Control, Representation, and Time Course," *Annual Review of Psychology*, Vol. 48, pp. 269–297.
Egly, R., Driver, J., and Rafal, R. D. (1994a), "Shifting Visual Attention between Objects and Locations: Evidence from Normal and Parietal Lesion Subjects," *Journal of Experimental Psychology: General*, Vol. 123, pp. 161–177.
Egly, R., Rafal, R. D., Driver, J., and Starrveveld, Y. (1994b), "Covert Orienting in the Split Brain Reveals Hemispheric Specialization for Object-Based Attention," *Psychological Science*, Vol. 5, pp. 380–383.
Eley, M. G. (1988), "Determining the Shapes of Land Surfaces from Topographical Maps," *Ergonomics*, Vol. 31, pp. 355–376.
Elzer, S., Green, N., and Carberry, S. (2003), "Exploiting Cognitive Psychology Research for Recognizing Intention in Information Graphics," paper presented at the Annual Conference of the Cognitive Science Society, Boston, August.
Endsley, M. R. (1995), "Measurement of Situation Awareness in Dynamic Systems," *Human Factors*, Vol. 37, No. 1, pp. 65–84.
Endsley, M. R., and Garland, D. J. (2000), "Situation Awareness Analysis and Measurement," Lawrence Erlbaum Associates, Mahwah, NJ.

Engle, R. W. (2002), "Working Memory Capacity as Executive Attention," *Current Directions in Psychological Science*, Vol. 11, pp. 19–23

Engle, R. W., Tuholski, S. W., Laughlin, J. E., and Conway, A. R. A. (1999), "Working Memory, Short-Term Memory, and General Fluid Intelligence: A Latent-Variable Approach," *Journal of Experimental Psychology: General*, Vol. 128, pp. 309–331.

Ericsson, K. A., and Kintsch, W. (1995), "Long-Term Working Memory," *Psychological Review*, Vol. 102, pp. 211–245.

Evans, L. (1991), *Traffic Safety and the Driver*, Van Nostrand Reinhold, New York.

Fadden, S., Ververs, P. M., and Wickens, C. D. (2001), "Pathway HUDS: Are They Viable?" *Human Factors*, Vol. 43, No. 2, pp. 173–193.

Finke, R. A., Ward, T. B., and Smith, S. M. (1992), *Creative Cognition*, MIT Press, Cambridge, MA.

Fisher, D. L., Coury, B. G., Tengs, T. O., and Duffy, S. A. (1989), "Minimizing the Time to Search Visual Displays: The Role of Highlighting," *Human Factors*, Vol. 31, No. 2, pp. 167–182.

Fisk, A. D., Ackerman, P. L., and Schneider, W. (1987), "Automatic and Controlled Processing Theory and Its Applications to Human Factors Problems," in *Human Factors Psychology*, P. A. Hancock, Ed., Elsevier Science, New York, pp. 159–197.

Fitts, P. M. (1966), "Cognitive Aspects of Information Processing, III: Set for Speed Versus Accuracy," *Journal of Experimental Psychology*, Vol. 71, pp. 849–857.

Fitts, P. M., and Peterson, J. R. (1964), "Information Capacity of Discrete Motor Responses," *Journal of Experimental Psychology*, Vol. 67, pp. 103–112.

Fitts, P. M., and Posner, M. A. (1967), *Human Performance*, Brooks/Cole, Pacific Palisades, CA.

Flach, J. M., Hancock, P. A., Caird, J., and Vicente, K. J., Eds. (1995), *Global Perspectives on the Ecology of Human–Machine Systems*, Lawrence Erlbaum Associates, Mahwah, NJ.

Flavell, J. H. (1979), "Metacognition and Cognitive Monitoring: A New Area of Cognitive Developmental Inquiry," *American Psychologist*, Vol. 34, pp. 906–911.

Fracker, M. L., and Wickens, C. D. (1989), "Resources, Confusions, and Compatibility in Dual Axis Tracking: Displays, Controls, and Dynamics," *Journal of Experimental Psychology: Human Perception and Performance*, Vol. 15, pp. 80–96.

Gathercole, S. E. (1997), "Models of Verbal Short-Term Memory," in *Cognitive Models of Memory*, M. A. Conway, Ed., MIT Press, Cambridge, MA, pp. 13–45.

Gathercole, S. E., and Baddeley, A. D. (1993), *Working Memory and Language*, Lawrence Erlbaum Associates Hove, East Sussex, England.

Gentner, D., and Stevens, A. L. (1983), *Mental Models*, Lawrence Erlbaum Associates, Mahwah, NJ.

Gibson, J. J. (1979), *The Ecological Approach to Visual Perception*, Houghton Mifflin, Boston.

Giffin, Gillam, B. (1980), "Geometrical Illusions," *Scientific American*, Vol. 242, pp. 102–111.

Gillan, D. J., Wickens, C. D., Hollands, J. G., and Carswell, C. M. (1998), "Guidelines for Presenting Quantitative Data in HFES Publications," *Human Factors*, Vol. 40, pp. 28–41.

Gold, J., Bennett, P. J., and Sekuler, A. B. (1999), "Signal But Not Noise Changes with Perceptual Learning," *Nature*, Vol. 402, pp. 176–178.

Gonzales, V. G., and Mark, G. (2004), "Constant Multi-Tasking Craziness: Managing Multiple Working Spheres," in *Human Factors of Computing Systems: CHI 04*, Association for Computing Machinery, New York, pp. 113–120.

Gopher, D. (1992), "The Skill of Attention Control: Acquisition and Execution of Attention Strategies," in *Attention and Performance XIV: Synergies in Experimental Psychology, Artificial Intelligence, and Cognitive Neuroscience—A Silver Jubilee*, D. Meyer and S. Kornblum, Eds., MIT Press, Cambridge, MA.

Graf, R., and Torrey, J. W. (1966), "Perception of Phrase Structure in Written Language," in *Proceedings of the Annual Convention of the American Psychological Association APA*, Washington, DC, pp. 83–84.

Graham, J. L. (1937), "Illusory Trends in the Observation of Bar Graphs," *Journal of Experimental Psychology*, Vol. 20, pp. 597–608.

Gray, W. D., and Fu, W. T. (2004), "Soft Constraints in Interactive Behavior: The Case of Ignoring Perfect Knowledge In-The-World for Imperfect Knowledge In-The-Head", *Cognitive Science*, Vol. 28, pp. 359–382.

Green, C., and Hummel, J. E. (2006), "Familiar Interacting Object Pairs Are Perceptually Grouped," *Journal of Experimental Psychology: Human Perception and Performance*, Vol. 32, pp. 1107–1119.

Green, D. M., and Swets, J. A. (1989), *Signal Detection Theory and Psychophysics*, Wiley, New York.

Gregory, R. L. (1980), "The Confounded Eye," in *Illusion in Nature and Art*, R. E. Gregory and E. H. Gombrich, Eds., Charles Scribner's Sons, New York.

Gugerty, L., and Brooks, J. (2001), "Seeing Where You Are Heading: Integrating Environmental and Egocentric Reference Frames in Cardinal Direction Judgments," *Journal of Experimental Psychology: Applied*, Vol. 7, No. 3, pp. 251–266.

Hancock, P., Flach, J., Caird, J., and Vicente, K., Eds. (1995), *Local Applications of the Ecological Approach to Human–Machine Systems*, Lawrence Erlbaum Associates, Mahwah, NJ.

Harris, D. H., and Chaney, F. D. (1969), *Human Factors in Quality Assurance*, Wiley, New York.

Hart, S. G., and Wickens, C. D. (1990), "Workload Assessment and Prediction," in *MANPRINT: An Approach to Systems Integration*, H. R. Booher, Ed., Van Nostrand Reinhold, New York, pp. 257–296.

Herrmann, D., Brubaker, B., Yoder, C., Sheets, V., and Tio, A. (1999), "Devices That Remind," in *Handbook of Applied Cognition*, F. T. Durso, Ed., Wiley, New York, pp. 377–407.

Hess, S. M., and Detweiler, M. C. (1995), "The Effects of Response Alternatives on Keeping-Track Performance," in *Proceedings of the 39th Annual Meeting of the Human Factors and Ergonomics Society*, Human Factors and Ergonomics Society, Santa Monica, CA, pp. 1390–1394.

Hettinger, L. J. (2002), "Illusory Self-Motion in Virtual Environment," in *Handbook of Virtual Environments: Design, Implementation, and Application*, K. M. Stanney, Ed., Lawrence Erlbaum Associates, Mahwah, NJ, pp. 471–491.

Hick, W. E. (1952), "On the Rate of Gain of Information," *Quarterly Journal of Experimental Psychology*, Vol. 4, pp. 11–26.

Hickox, J. C., and Wickens, C. D. (1999), "Effects of Elevation Angle Disparity, Complexity, and Feature Type on Relating Out-of-Cockpit Field of View to an Electronic Cartographic Map," *Journal of Experimental Psychology: Applied*, Vol. 5, No. 3, pp. 284–301.

Ho, C. Y., Nikolic, M. I., Waters, M., and Sarter, N. B. (2004), "Not Now! Supporting Interruption Management by Indicating the Modality and Urgency of Pending Tasks", *Human Factors*, Vo. 46, pp. 399–410.

Hochberg, J. (1986), "Representation of Motion and Space in Video and Cinematic Displays," in *Handbook of Perception and Human Performance*, Vol. 1, K. Boff, R. Kaufman, and J. Thomas, Eds., Wiley Interscience, New York, pp. 22-1–22-64.

Hochberg, J. (1998), "Gestalt Theory and Its Legacy," in *Perception and Cognition at Century's End*, J. Hochberg, Ed., Academic, New York, pp. 253–306.

Hoffman, R., Crandall, B., and Shadbolt, N. (1998), "Use of the Critical Decision Method to Elicit Expert Knowledge". *Human Factors*, Vol. 40, pp. 254–276.

Hollands, J. G., and Dyre, B. P. (2000), "Bias in Proportion Judgments: The Cyclical Power Model," *Psychological Review*, Vol. 107, No. 3, pp. 500–524.

Hollands, J. G., and Spence, I. (1992), "Judgments of Change and Proportion in Graphical Perception," *Human Factors*, Vol. 34, No. 3, pp. 313–334.

Holohan, C. J., Culler, R. E., and Wilcox, B. L. (1978), "Effects of Visual Distraction on Reaction Time in a Simulated Traffic Environment," *Human Factors*, Vol. 20, No. 4, pp. 409–413.

Horrey, W. J., and Wickens, C. D. (2006), "The Impact of Cell Phone Conversations on Driving: A Meta-Analytic Approach," *Human Factors*, Vol. 48, No. 1, pp. 196–205.

Horrey, W. J., Wickens, C. D., and Consalus, K. P. (2006), "Modeling Drivers' Visual Attention Allocation While Interacting with In-Vehicle Technologies," *Journal of Experimental Psychology: Applied*, Vol. 12, No. 2, pp. 67–78.

Huestegge, L., and Phillipp, A. M, (in press), "Effects of Spatial Compatibility on Integration Processes in Graph Comprehension," *Attention, Perception & Psychophysics*.

Hutchins, E. L., Hollan, J. D., and Norman, D. A. (1985), "Direct Manipulation Interfaces," *Human–Computer Interaction*, Vol. 1, No. 4, pp. 311–338.

Hyman, R. (1953), "Stimulus Information as a Determinant of Reaction Time," *Journal of Experimental Psychology*, Vol. 45, pp. 423–432.

Iani, C., and Wickens, C. D. (2007), "Factors Affecting Task Management in Aviation," *Human Factors*, Vol. 49, No. 1, pp. 16–24

Jagacinski, R. J., and Flach, J. M. (2003), *Control Theory for Humans*, Lawrence Erlbaum Associates, Mahwah, NJ.

James, W. (1890), *The Principles of Psychology*, Vol. 1, Holt, New York.

Jenkins, D., Stanton, N., Salmon, P., and Walder, G. (2009), *Cognitive Work Analysis: Coping with Complexity*, Ashgate, Averbury VT.

Johnson, A., and Proctor, R. W. (2004), *Attention Theory and Practice*, Sage, Thousand Oaks, CA.

Johnson, S. L., and Roscoe, S. N. (1972), "What Moves, the Airplane or the World?" *Human Factors*, Vol. 14, pp. 107–129.

Jolicoeur, P., and Ingleton, M. (1991), "Size Invariance in Curve tracing," *Memory & Cognition*, Vol. 19, No. 1, pp. 21–36.

Jones, D. G., and Endsley, M. R. (1996), "Sources of Situation Awareness Errors in Aviation," *Aviation, Space, and Environmental Medicine*, Vol. 67, No. 6, pp. 507–512.

Just, M. A., and Carpenter, P. A. (1987), *The Psychology of Reading and Language Comprehension*, Allyn and Bacon, Boston.

Kahneman, D. (1973), *Attention and Effort*, Prentice-Hall, Englewood Cliffs, NJ.

Kahneman, D., and Klein, G. (2009), "Conditions for Intuitive Expertise," *American Psychologist*, Vol. 64, pp. 215–226

Kahneman, D., and Treisman, D. (1984), "Changing Views of Attention and Automaticity," in *Varieties of Attention*, R. Parasuraman, R. Davies, and J. Beatty, Eds., Academic, New York, pp. 29–61.

Kintsch, W., and Keenan, J. (1973), "Reading Rate and Retention as a Function of the Number of Propositions in the Base Structure of Sentences," *Cognitive Psychology*, Vol. 5, pp. 257–274.

Kintsch, W., and Van Dijk, T. A. (1978), "Toward a Model of Text Comprehension and Reproduction," *Psychological Review*, Vol. 85, pp. 363–394.

Kintsch, W., and Vipond, P. (1979), "Reading Comprehension and Readability in Educational Practice and Psychological Theory," in *Perspectives on Memory Research*, L. G. Nilsson, Ed., Lawrence Erlbaum Associates, Mahwah, NJ.

Kirlik, A., Miller, A., and Jagacinski, R. J. (1993), "Supervisory Control in a Dynamic and Uncertain Environment: A Process Model of Skilled Human–Environment Interaction," *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 23, No. 4, pp. 929–952.

Klein, G., and Crandall, B. W. (1995), "The Role of Simulation in Problem Solving and Decision Making," in *Local Applications of the Ecological Approach to Human–Machine Systems*, P. Hancock, J. Flach, J. Caird, and K. Vicente, Eds., Lawrence Erlbaum Associates, Mahwah, NJ.

Klein, G. A., Orasanu, J., Calderwood, R., and Zsambok, E., Eds. (1993), *Decision Making in Action: Models and Methods*, Ablex, Norwood, NJ.

Kleinman, and Pattipati, (1991), "A Review of Engineering Models of Information Processing and Decision Making in Multitask Supervisory Control," in *Multiple Task Performance*, D. Damos, Ed., Taylor & Francis, London.

Kosslyn, S. M. (1987), "Seeing and Imagining in the Cerebral Hemispheres: A Computational Approach," *Psychological Review*, Vol. 94, pp. 148–175.

Kosslyn, S. M. (2006), *Graph Design for the Eye and Mind*, Oxford University Press, New York.

Kundel, H. L., and Nodine, C. F. (1978), "Studies of Eye Movements and Visual Search in Radiology," in *Eye Movements and Higher Psychological Functions*, J. Senders, D. Fisher, and R. Monty, Eds., Lawrence Erlbaum Associates, Mahwah, NJ, pp. 317–328.

Langolf, C. D., Chaffin, D. B., and Foulke, S. A. (1976), "An Investigation of Fitts' Law Using a Wide Range of Movement Amplitudes," *Journal of Motor Behavior*, Vol. 8, pp. 113–128.

Latorella, K. A. (1996), "Investigating Interruptions—An Example from the Flightdeck" *Proceedings of the 40th Annual Meeting HFES*, Human Factors Society, Santa Monica, CA.

Layton, C., Smith, P. J., and McCoy, C. E. (1994), "Design of a Cooperative Problem-Solving System for En-Route Flight Planning: An Empirical Evaluation," *Human Factors*, Vol. 36, No. 4, pp. 94–119.

Lee, J. D. (2005), "Driving Safety,"in *Reviews of Human Factors and Ergonomics*, R. S. Nickerson, Ed., Human Factors and Ergonomics Society, Santa Monica, CA, pp. 172–218.

Leibowitz, H. W. (1985), "Grade Crossing Accidents and Human Factors Engineering," *American Scientist*, Vol. 73, pp. 558–562.

Levine, D. T., Momen, N., Drivdahl, S. B., and Simons, D. J. (2000), "Change Blindness Blindness: The Metacognitive Error of Overestimating Change-Detection Ability," *Visual Cognition*, Vol. 7, pp. 397–412.

Levine, M. (1982), "You-Are-Here Maps: Psychological Considerations," *Environment and Behavior*, Vol. 14, pp. 221–237.

Levine, M. (1988), *Effective Problem Solving*, Prentice-Hall, Englewood Cliffs, NJ.

Liu, Y., Feyen, R., and Tsimhoni, O. (2006). "Queueing Network-Model Human Processor (QN-MHP): A Computational Architecture for Multitask Performance in Human-Machine Systems," *ACM Transactions on Computer-Human Interaction*, Vol. 13, No. 1. pp. 37–70.

Loftus, G., Dark, V., and Williams, D. (1979), "Short-Term Memory Factors in Ground Controller/Pilot Communication," *Human Factors*, Vol. 21, pp. 169–181.

Logie, R. H. (1995), *Visuo-Spatial Working Memory*, Lawrence Erlbaum Associates, Hove, East Sussex, England.

Loukopopolous, L. Dismukes, K., and Barshi, I. (2009), *The Multi Tasking Myth*, Ashgate, Avebury, VT.

Lusted, L. B. (1976), "Clinical Decision Making," in *Decision Making and Medical Care*, D. Dombal and J. Grevy, Eds., North-Holland, Amsterdam.

Macedo, J., Kaber, D., Endsley, M., Powanusorn, P., and S. Myung (1998), "The Effect of Automated Compensation for Incongruent Axes on Teleoperator Performance," *Human Factors*, Vol. 40, pp. 541–553.

Macmillan, N. A., and Creelman, C. D. (2005), *Detection Theory: A User's Guide*. Lawrence Erlbaum, Mahwah, NJ.

Maltz, M., and Shinar, D. (2003), "New Alternative Methods of Analyzing Human Behavior in Cued Target Acquisition," *Human Factors*, Vol. 45, No. 2, pp. 281–295.

Massaro, D. W. (1979), "Letter Information and Orthographic Context in Word Perception," *Journal of Experimental Psychology: Human Perception and Performance*, Vol. 5, pp. 595–609.

Mayer, R. (2007), "Task Based Guidelines for Multi-Media Instructions," in *Reviews of Human Factors & Ergonomics*, Vol. 3, D. Boehm-Davis, Ed., Human Factors Society, Santa Monica, CA.

Mayer, R. E. (1983), *Thinking, Problem Solving, Cognition*, W. H. Freeman, San Francisco.

Mayer, R. E. (1999), "Fifty Years of Creativity Research," in *Handbook of Creativity*, R. J. Sternberg, Ed., Cambridge University Press, New York, pp. 449–460.

McCarley, J. M., Kromer, A. F., Wickens, C. D., Vidoni, E. D., and Boot, W. R. (2004), "Visual Skills in Airport Security Screening," *Psychological Science*, Vol. 15, pp. 302–306.

McClelland, J. L., and Rumelhart, D. E. (1981), "An Interactive Activation Model of Context Effects in Letter Perception, I: An Account of Basic Findings," *Psychological Review*, Vol. 88, pp. 375–407.

McDaniel, M. A., and Einstein, G. O. (2007), *Prospective Memory: An Overview and Synthesis of an Emerging Field*, Sage, Thousand Oaks, CA.

McFarlane, D. C., and Latorella, K. A. (2002), "The Score and Importance of Human Interruption in Human–Computer Interface Design," *Human–Computer Interaction*, Vol. 17, No. 1, pp. 1–61.

McGuirl, J. M., and Sarter, N. B. (2006), "Supporting Trust Calibration and the Effective use of Decision Aids by Presenting Dynamic System Confidence Information," *Human Factors*, Vol. 48, No. 4, pp. 656–665.

McKoon, G., and Ratcliff, R. (1992), "Inference during Reading," *Psychological Review*, Vol. 99, pp. 440–466.

McRuer, D. (1980), "Human Dynamics in Man–Machine Systems," *Automatica*, Vol. 16, pp. 237–253.

Meyer, D. E., and Kieras, D. E. (1997), "A Computational Theory of Executive Cognitive Processes and Multiple-Task Performance: Part 1: Basic Mechanisms," *Psychological Review*, Vol. 104, pp. 3–65.

Milkman, K., Clugh, D., and Bazerman, M. (2009), "How Can Decision Making Be Improved?" *Perspectives on Psychological Science*, Vol. 4, pp. 379–383.

Miller, G. A. (1956), "The Magical Number Seven Plus or Minus Two: Some Limits on Our Capacity for Processing Information," *Psychological Review*, Vol. 63, pp. 81–97.

Miller, G. A., Galanter, E., and Pribram, K. H. (1960), *Plans and the Structure of Behavior*, Holt, Rinehart and Winston, New York.

Monsell, S. (2003), "Task Switching," *Trends in Cognitive Science*, Vol. 7, pp. 134–140.

Moray, N. (1981), "The Role of Attention in the Detection of Errors and the Diagnosis of Errors in Man–Machine Systems," in *Human Detection and Diagnosis of System Failures*, J. Rasmussen and W. Rouse, Eds., Plenum, New York.

Moray, N. (1986), "Monitoring Behavior and Supervisory Control," in *Handbook of Perception and Performance*, Vol. 2, K. R. Boff, L. Kaufman, and J. P. Thomas, Eds., Wiley, New York, pp. 40-1–40-51.

Moray, N., Lee, J., Vicente, K., Jones, B. G., and Rasmussen, J. (1994), "A Direct Perception Interface for Nuclear Power Plants," in *Proceedings of the 38th Annual Meeting of the Human Factors and Ergonomics Society*, Human Factors and Ergonomics Society, Santa Monica, CA, pp. 481–485.

Mori, H., and Hayashi, Y. (1995). Visual Interference with Users' Tasks on Multi-Window Systems, *International Journal of Human–Computer Interaction*, Vol. 7, pp. 329–340.

Neisser, U. (1967), *Cognitive Psychology*, Prentice-Hall, Englewood Cliffs, NJ.

Neisser, U., Novick, R., and Lazar, R. (1964), "Searching for Novel Targets," *Perceptual and Motor Skills*, Vol. 19, pp. 427–432.

Nickerson, R. (1998), "Confirmation Bias: AUbiquitous Phenomenon," *Review of General Psychology*, Vol. 2, pp. 175–220

Nickerson, R. S. (1999), "Enhancing Creativity," in *Handbook of Creativity*, R. J. Sternberg, Ed., Cambridge University Press, New York, pp. 392–430.

Norman, D. (1988), *The Psychology of Everyday Things*, Basic Books, New York.

Norman, D. A. (1981), "Categorization of Action Slips," *Psychological Review*, Vol. 88, pp. 1–15.

North, C. (2006), "Information Visualization,"in *Handbook of Human Factors & Ergonomics*, 3rd., G. Salvendy, Ed., Wiley, Hoboken, NJ.

Oliva, A., and Torralba, A. (2010), "The Role of Context in Object Recognition," *Trends in Cognitive Science*, Vol. 11, No. 12, pp. 620–627.

Olmos, O., Liang, C.-C., and Wickens, C. D. (1997), "Electronic Map Evaluation in Simulated Visual Meteorological Conditions," *International Journal of Aviation Psychology*, Vol. 7, No. 1, pp. 37–66.

Olmos, O., Wickens, C. D., and Chudy, A. (2000), "Tactical Displays for Combat Awareness: An Examination of Dimensionality and Frame of Reference Concepts and the Application of Cognitive Engineering," *International Journal of Aviation Psychology*, Vol. 10, No. 3, pp. 247–271.

Orasanu, J. M. (1993), "Decision-Making in the Cockpit," in *Cockpit Resource Management*, E. L. Wiener, B. G. Kanki, and R. L. Helmreich, Eds., Academic, San Diego, CA, pp. 137–173.

Orasanu, J., and Fischer, U. (1997), "Finding Decisions in Natural Environments: The View from the Cockpit," in *Naturalistic Decision Making*, C. Zsambok and G. Klein, Eds., Lawrence Erlbaum Associates, Mahwah, NJ, pp. 343–357.

Osborne, D. W., and Ellingstad, V. S. (1987), "Using Sensor Lines to Show Control–Display Linkages on a Four Burner Stove," in *Proceedings of the 31st Annual Meeting of the Human Factors Society*, Human Factors Society, Santa Monica, CA, pp. 581–584.

Paas, F., Renkl, A., and Sweller, J. (2003), "Cognitive Load Theory and Instructional Design: Recent Developments," *Educational Psychologist*, Vol. 31, pp. 1–5.

Palmer, S. E. (1975), "The Effects of Contextual Scenes on the Identification of Objects," *Memory and Cognition*, Vol. 3, pp. 519–526.

Parasuraman, R., Davies, R., and Beatty, J., Eds. (1984), *Varieties of Attention*, Academic, New York.

Parasuraman, R., Hancock, P. A., and Obofinbaba, O. (1997), "Alarm Effectiveness in Driver Centered Collision Warning Systems," *Ergonomics*, Vol. 40, pp. 390–399.

Parasuraman, R., Sheridan, T. B., and Wickens, C. D. (2000), "A Model for Types and Levels of Human Interaction with Automation," *IEEE Transactions on Systems, Man, & Cybernetics: Part A: Systems and Humans*, Vol. 30, No. 3, pp. 286–297.

Parasuraman, R., Sheridan, T., and Wickens, C. D. (2008), "Situation Awareness, Mental Workload, and Trust in Automation: Viable, Empirically Supported Cognitive Engineering Constructs," *Cognitive Engineering and Decision Making*, Vol. 2, pp. 140–160.

Pashler, H. E. (1998), *The Psychology of Attention*, MIT Press, Cambridge, MA.

Patterson, R. (1997), "Visual Processing of Depth Information in Stereoscopic Displays," *Human Factors*, Vol. 17, pp. 69–74.

Payne, S. J. (1995), "Naive Judgments of Stimulus-Response Compatibility," *Human Factors*, Vol. 37, No. 3, pp. 495–506.

Penrose, J. M. (2008), "Annual Report Graphic Use: A Review of the Literature," *Journal of Business Communication*, Vol. 45, No. 2, pp. 158–180.

Peterson, L. R., and Peterson, M. J. (1959), "Short-Term Retention of Individual Verbal Items," *Journal of Experimental Psychology*, Vol. 58, pp. 193–198.

Pew, R. W., and Baron, S. (1978), "The Components of an Information Processing Theory of Skilled Performance Based on an Optimal Control Perspective," in *Information Processing in Motor Control and Learning*, G. E. Stelmach, Ed., Academic, New York.

Phillips, J. G., Triggs, T. J., and Meehan, J. W. (2003), "Conflicting Directional and Locational Cues Afforded by Arrowhead Cursors in Graphical User Interfaces," *Journal of Experimental Psychology: Applied*, Vol. 9, pp. 75–87.

Pomerantz, J. R. (1981), "Perceptual Organization in Information Processing," in *Perceptual Organization*, M. Kubovy and J. R. Pomerantz, Eds., Lawrence Erlbaum Associates, Mahwah, NJ, pp. 141–180.

Pomerantz, J. R., and Kubovy, M. (1986), "Theoretical Approaches to Perceptual Organization," in *Handbook of Perception and Human Performance*, Vol. II, K. R. Boff, L. Kaufman, and J. P. Thomas, Eds., Wiley, New York, pp. 36-1–36-46.

Pomerantz, J. R., and Pristach, E. A. (1989), "Emergent Features, Attention, and Perceptual Glue in Visual Form Perception," *Journal of Experimental Psychology: Human Perception and Performance*, Vol. 15, pp. 635–649.

Posner, M. I. (1978), *Chronometric Explorations of the Mind*, Lawrence Erlbaum Associates, Mahwah, NJ.

Postle, B. R., Idzikowski, C., Salac, S. D., Logie, R. H., and Baddeley, A. D. (2006), "The Selective Disruption of Spatial Working Memory by Eye Movements," *Quarterly Journal of Experimental Psychology*, Vol. 59, No. 1, pp. 100–120.

Poulton, E. C. (1985), "Geometric Illusions in Reading Graphs," *Perception and Psychophysics*, Vol. 37, pp. 543–548.

Previc, F., and Ercoline, W. (2004), *Spatial Orientation in Aviation*, American Institute of Aeronautics and Astronautics, Reston, VA.

Previc, F. H. (1998), "The Neuropsychology of 3-D Space," *Psychological Bulletin*, Vol. 124, pp. 123–164.

Prinzel, L., and Wickens C. D., Eds. (2008–2009), Special Issue on Synthetic Vision Displays, *International Journal of Aviation Psychology*, Vol. 38, No. 4; Vol. 39, No. 1.

Raby, M., and Wickens, C. D. (1994), "Strategic Workload Management and Decision Biases in Aviation," *International Journal of Aviation Psychology*, Vol. 4, No. 3, pp. 211–240.

Rasmussen, J. (1981), "Models of Mental Strategies in Process Control," in *Human Detection and Diagnosis of System Failures*, J. Rasmussen and W. Rouse, Eds., Plenum, New York.

Rasmussen, J. (1986), *Information Processing and Human–Machine Interaction: An Approach to Cognitive Engineering*, North-Holland, New York.

Rasmussen, J., Pejtersen, A.-M., and Goodstein, L. (1995), *Cognitive Engineering: Concepts and Applications*, Wiley, New York.

Reason, J. (1990), *Human Error*, Cambridge University Press, New York.

Reason, J. (1997), *Managing the Risks of Organizational Accidents*, Ashgate, Brookfield, VT.

Reason, J. (2008), *The Human Contribution*, MIT Press, Cambridge, MA.

Reder, L. M. (1996), *Implicit Memory and Metacognition*, Lawrence Erlbaum Associates, Mahwah, NJ.

Regan, M., Lee, J. D., and Young, K. (2009), *Driver Distraction: Theories, Effects and Mitigation*, CRC Press, Boca Raton, FL.

Reicher, G. M. (1969), "Perceptual Recognition as a Function of Meaningfulness of Stimuli Materials," *Journal of Experimental Psychology*, Vol. 81, pp. 275–280.

Remington, R. W., Johnston, J. C., Ruthruff, E., Gold, M., and Romera, M. (2000), "Visual Search in Complex Displays: Factors Affecting Conflict Detection by Air Traffic Controllers," *Human Factors*, Vol. 42, No. 3, pp. 349–366.

Rensink, R. A. (2002), "Change Detection," *Annual Review of Psychology*, Vol. 53, pp. 245–277.

Robertson, G., Czerwinski, M., Fisher, D., and Lee, B. (2009), "Human Factors of Information Visualization," *Reviews of Human Factors & Ergonomics*, Vol. 5, pp. 41–81.

Rogers, D., and Monsell, S. (1995), "Costs of a Predictable Switch between Simple Cognitive Tasks," *Journal of Experimental Psychology: General*, Vol. 124, pp. 207–231.

Roscoe, S. N. (1968), "Airborne Displays for Flight and Navigation," *Human Factors*, Vol. 18, pp. 321–332.

Saks, M. J., Risinger, D. M., Rosenthal, R., and Thompson, W. C. (2003), "Context Effects in Forensic Science: A Review and Application of the Science of Science to Crime Laboratory Practice in the United States," *Science & Justice*, Vol. 43, pp. 77–90.

Salvucci, D., and Taatgen, N. A. (2011), *The Multi-Tasking Mind*, Oxford University Press, Oxford.

Sanchez, C. A., and Wiley, J. (2009), "To Scroll Or Not to Scroll: Scrolling, Working Memory Capacity, and Comprehending Complex Texts," *Human Factors*, Vol. 51, No. 5, pp. 730–738.

Sanders, M. S., and McCormick, E. J. (1993), *Human Factors in Engineering and Design*, 7th ed., McGraw-Hill, New York.

Sanderson, P. M. (1989), "The Human Planning and Scheduling Role in Advanced Manufacturing Systems: An Emerging Human Factors Domain," *Human Factors*, Vol. 31, pp. 635–666.

Sarter, N. (2007), "Multiple Resource Theory as a Basis for Multi-Modal Interface Design," in *Attention: From Theory to Practice*, A. F. Kramer, D. A. Wiegmann, and A. Kirlik, Eds., Oxford University Press, Oxford.

Schank, R. C., and Abelson, R. (1977), *Scripts, Plans, Goals, and Understanding*, Lawrence Erlbaum Associates, Mahwah, NJ.

Schneider, W., and Shiffrin, R. (1977), "Controlled and Automatic Human Information Processing, I: Detection, Search, and Attention," *Psychological Review*, Vol. 84, pp. 1–66.

Schneiderman, B. (2009), "Creativity Support Tools: A Grand Challenge for HCI Researchers," in *Engineering the User Interface*, M. Redondo, Ed., Springer, London, pp. 1–9.

Scholl, B. (2007), *Object Perception*, MIT Press, Cambridge, MA.

Schraw, G., and Moshman, D. (1995), "Metacognitive Theories," *Educational Psychology Review*, Vol. 7, No. 4, pp. 351–371.

Schutte, P. C., and Trujillo, A. C. (1996), "Flight Crew Task Management in Nonnormal Situations," in *Proceedings of the 40th Annual Meeting of the Human Factors and Ergonomics Society*, Human Factors and Ergonomics Society, Santa Monica, CA.

Schwaninger, A., and Wales, A. W. J. (2009), "One Year Later: How Screener Performance Improves in X-ray Luggage Search with Computer-Based Training," in *Contemporary Ergonomics*, P. D. Bust, Ed., Taylor and Francis, London, pp. 381–389.

Schwarz, N., and Vaughan, L. (2002), "The Availability Heuristic Revisited," in *Heuristics and Biases*, T. Gilovich, D. Griffin, and D. Kahneman, Eds., Cambridge University Press, Cambridge.

Senders, J. W. (1980), "Visual Scanning Processes," unpublished doctoral thesis, University of Tilburg, Tilburg, The Netherlands.

Shah, P., and Iyiri, A. (2005), *Handbook of Visual Spatial Thinking*, Cambridge University Press, Cambridge.

Shalin, V. L., and Bertram, D. A. (in press), "Functions of Expertise in a Medical Intensive Care Unit," *Journal of Experimental and Theoretical Artificial Intelligence: Special Issue on Expertise*.

Shen, M., Carswell, M., Santhanam, R., and Bailey, K. (in press),"Can Decision Makers Be Advised to Choose Appropriate Display Formats?"

Shiffrar, M., and Freyd, J. J. (1990), "Apparent Motion of the Human Body," *Psychological Science*, Vol. 1, No. 4, pp. 257–264.

Shinar, D., Rockwell, T. H., and Malecki, J. A. (1980), "The Effects of Changes in Driver Perception on Road Curve Negotiation," *Ergonomics*, Vol. 23, pp. 263–275.

Simons, D., and Levin, D. (1997), "Change Blindness," *Trends in Cognitive Science*, Vol. 1, pp. 261–267.

Smallman, H. S., and St. John, M. S.T. (2005), "Naive Realism: Misplaced Faith in Realistic Displays," *Ergonomics in Design*, Vol. 13, No. 3, pp. 6–13.

Smith, K. U. (1962), *Delayed Sensory Feedback and Balance*, Saunders, Philadelphia.

Smith, P., Bennett, K., and Stone, R. (2006), "Representational Aiding to Support Problem Solving Tasks,"in *Reviews of Human Factors and Ergonomics*, Vol. 2, R. C. Williges, Ed., Human Factors Society, Santa Monica, CA.

Smith, S. M. (1995), "Getting Into and Out of Mental Ruts: A Theory of Fixation, Incubation, and Insight," in *The Nature of Insight*, R. J. Sternberg and J. F. Davidson, Eds., MIT Press, Cambridge, MA, pp. 229–251.

Sorkin, R. (1989), "Why Are People Turning Off Our Alarms?" *Human Factors Bulletin*, Vol. 32, pp. 3–4.

Sorkin, R. D., and Woods, D. D. (1985), "Systems with Human Monitors, a Signal Detection Analysis," *Human–Computer Interaction*, Vol. 1, pp. 49–75.

St. Johns, M., and Manes, D. I. (2002), :"Making Unreliable Automation Useful," in*Proceedings of the 46th Annual Meeting of the Human Factors and Ergonomics Society*, Human Factors and Ergonomics Society, Santa Monica, CA.

St. John, M., Smallman, H. S., and Manes, D. I. (2005), "Recovery from Interruptions to a Dynamic Monitoring Task: The Beguiling Utility of Instant Replay," in *Human Factors and Ergonomics Society Annual Meeting*

Proceedings, Human Factors and Ergonomics Society, Santa Monica, CA, pp. 473–477.

Stanton, N., Ed. (1994), *Human Factors in Alarm Design*, Taylor & Francis, Bristol, PA.

Stelzer E. M., and Wickens, C. D. (2006). "Pilots Strategically Compensate for Display Enlargements in Surveillance and Flight Control Tasks," *Human Factors*, Vol. 48, No. 1, pp. 166–181.

Sternberg, S. (1969), "The Discovery of Processing Stages: Extension of Donders' Method," *Acta Psychologica*, Vol. 30, pp. 276–315.

Sternberg, R. J., and Powell, J. S. (1983), "Comprehending Verbal Comprehension," *American Psychologist*, Vol. 38, pp. 878–893.

Strayer, D. L., Wickens, C. D., and Braune, R. (1987), "Adult Age Differences in the Speed and Capacity of Information Processing, II: An Electrophysiological Approach," *Psychology and Aging*, Vol. 2, pp. 99–110.

Streeter, L. A., Vitello, D., and Wonsiewicz, S. A. (1985), "How to Tell People Where to Go: Comparing Navigational Aids," *International Journal on Man–Machine Studies*, Vol. 22, pp. 549–562.

Summala, H. (2000), "Brake Reaction Times and Driver Behavior Analysis," *Transportation Human Factors*, Vol. 2, pp. 217–226.

Taleb, N. (2007), *The Black Swan*.

Tanner, W. P., and Swets, J. A. (1954), "A Decision-Making Theory of Visual Detection," *Psychological Review*, Vol. 61, pp. 401–409.

Taylor, H. Brunye, T., and Taylor, S. (2008), "Spatial Mental Representation: Implications for Navigation System Design," in) *Reviews of Human factors & Ergonomics*, Vol.4, C. M. Carswell, Ed., Human Factors and Ergonomics Society, Santa Monica, CA.

Tenney, Y., and Pew, R. W., (2006), "Situation Awareness Catches On: What? So What? Now What?" in *Reviews of Human Factors & Ergonomics*, Vol. 3, R. Williges, Ed., Human Factors and Ergonomics Society, Santa Monica, CA.

Thorndyke, P. W. (1980, December), "Performance Models for Spatial and Locational Cognition," Technical Report R-2676-ONR, Rand, Washington, DC.

Thorndyke, P. W., and Hayes-Roth, B. (1982), "Differences in Spatial Knowledge Acquired from Maps and Navigation," *Cognitive Psychology*, Vol. 14, pp. 560–589.

Trafton, G., and Monk, C. (2007), "Task Interruptions," in *Reviews of Human Factors & Ergonomics*, Vol. 3, D. Boehm-Davis, Ed., Human Factors Society, Santa Monica, CA.

Trafton, G., Altman, E., Brock, D., and Mintz, F. E. (2003), "Preparing to Resume an Interrupted Tasks: Effects of Prospective Goal Encoding and Retrospective Rehearsal," *International Journal of Human Computer Studies*, Vol. 58, pp. 582–602

Travis, D. (1991), *Effective Color Displays: Theory and Practice*, Academic, New York.

Treisman, A. (1986), "Properties, Parts, and Objects," in *Handbook of Perception and Human Performance*, Vol. II, K. R. Boff, L. Kaufman, and J. P. Thomas, Eds., Wiley, New York, pp. 31-1–35-70.

Treisman, A. (1993), "The Perception of Features and Objects," in *Attention, Selection, Awareness, and Control: A Tribute to Donald Broadbent*, A. D. Baddeley and L. Weiskrantz, Eds., Clarendon, Oxford.

Treisman, A., Kahneman, D., and Burkell, J. (1983), "Perceptual Objects and the Cost of Filtering," *Perception and Psychophysics*, Vol. 33, pp. 527–532.

Tulga, M. K., and Sheridan, T. B. (1980), "Dynamic Decisions and Workload in Multitask Supervisory Control," *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 10, pp. 217–232.

Tulving, E., Mandler, G., and Baumal, R. (1964), "Interaction of Two Sources of Information in Tachistoscopic Word Recognition," *Canadian Journal of Psychology*, Vol. 18, pp. 62–71.

Tversky, A., and Kahneman, D. (1974), "Judgment under Uncertainty: Heuristics and Biases," *Science*, Vol. 185, pp. 1124–1131.

Veenman, M. V. J., Hout-Wolters, van B. H. A. M., and Afflerbach, P. (2006), "Metacognition and Learning: Conceptual and Methodological Considerations," *Metacognition and Learning*, Vol. 1, pp. 3–14.

Vicente, K. J. (1999), *Cognitive Work Analysis*, Lawrence Erlbaum Associates, Mahwah, NJ.

Vicente, K. J. (2002), "Ecological Interface Design: Progress and Challenges," *Human Factors*, Vol. 44, pp. 62–78.

Vicente, K., and Rasmussen, J. (1992), "Ecological Interface Design: Theoretical Foundations," *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 22, pp. 589–606.

Vicente, K. J., Christofferson, K., and Pereklita, A. (1995), "Supporting Operator Problem-Solving through Ecological Interface Designs," *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 25, No. 4, pp. 529–545.

Vu, K., and Proctor, R. W. (2003), "Naive and Experienced Judgments of Stimulus-Response Compatibility: Implications for Interface Design," *Ergonomics*, Vol. 46, No. 3, pp. 169–187.

Wall, S. A., and Brewster, S. A. (2003),"Assessing Haptic Properties for Data Representation," paper presented at theConference on Human Factors in Computing Systems: CHI '03 extended abstracts on Human factors in computing systems, April 5–10, Ft. Lauderdale, FL, pp. 858–859.

Wallsten, T. S., Ed. (1980), *Cognitive Processes in Choice and Decision Behavior*, Lawrence Erlbaum Associates, Mahwah, NJ.

Wang, X., Zhang, Q., Han, Q., Yang, R., Carswell, M., Seales, B., and Sutton, E. (2009), "Endoscopic Video Texture Mapping on Pre-Built 3D Anatomical Objects without Camera Tracking," *IEEE Transactions on Medical Imaging*, Vol. 7, No. 7, pp. 1–12.

Warm, J., Ed. (1984), *Sustained Attention in Human Performance*, Wiley, New York.

Warm, J., Parasuraman, R., and Matthews, G. (2008), "Vigilance Requires Hard Mental Work and Is Stressful," *Human Factors*, Vol. 50, No. 3, pp. 433–441.

Warren, D. H., Rossano, M. J., and Wear, T. D. (1990), "Perception of Map–Environment Correspondence: The Roles of Features and Alignment," *Ecological Psychology*, Vol. 2, pp. 131–150.

Wetherell, A. (1979), "Short-Term Memory for Verbal and Graphic Route Information," in *Proceedings of the 23rd Annual Meeting of the Human Factors Society*, Human Factors Society, Santa Monica, CA.

Whitaker, L. A., and CuQlock-Knopp, V. G. (1995), "Human Exploration and Perception in Off-Road Navigation," in *Local Applications of the Ecological Approach to Human–Machine Systems*, P. A. Hancock, J. M. Flach,

J. Caird, and K. J. Vicente, Eds., Lawrence Erlbaum Associates, Mahwah, NJ.

Wickelgren, W. A. (1964), "Size of Rehearsal Group in Short-Term Memory," *Journal of Experimental Psychology*, Vol. 68, pp. 413–419.

Wickelgren, W. A. (1977), "Speed–Accuracy Tradeoff and Information Processing Dynamics," *Acta Psychologica*, Vol. 41, pp. 67–85.

Wickens, C. D. (1984), *Engineering Psychology and Human Performance*, 1st ed., Charles Merrill, Columbus, OH.

Wickens, C. D. (1986), "The Effects of Control Dynamics on Performance," in *Handbook of Perception and Performance*, Vol. II, K. Boff, L. Kaufman, and J. Thomas, Eds., Wiley, New York, pp. 39-1–39-60.

Wickens, C. D. (1991), "Processing Resources and Attention," in *Multiple Task Performance*, D. Damos, Ed., Taylor & Francis, London.

Wickens, C. D. (1992), *Engineering Psychology and Human Performance*, 2nd ed., HarperCollins, New York.

Wickens, C. D. (1993), "Cognitive Factors in Display Design," *Journal of the Washington Academy of Sciences*, Vol. 83, No. 4, pp. 179–201.

Wickens, C. D. (1999), "Frames of Reference for Navigation," in *Attention and Performance*, Vol. 16, D. Gopher and A. Koriat, Eds., Academic, Orlando, FL, pp. 113–144.

Wickens, C. D. (2000), "The When and How of Using 2-D and 3-D Displays for Operational Tasks," in *Proceedings of the IEA2000/HFES2000 Congress*, Human Factors and Ergonomics Society, Santa Monica, CA, pp. 3-403–3-406.

Wickens, C. D. (2002), "Multiple Resources and Performance Prediction," *Theoretical Issues in Ergonomic Science*, Vol. 3, No. 2, pp. 159–177.

Wickens, C. D. (2003a), "Aviation Displays," in *Principles and Practices of Aviation Psychology*, P. Tsang and M. Vidulich, Eds., Lawrence Erlbaum Associates, Mahwah, NJ, pp. 147–199.

Wickens, C. D. (2003b), "Pilot Actions and Tasks: Selections, Execution, and Control," in *Principles and Practices of Aviation Psychology*, P. Tsang and M. Vidulich, Eds., Lawrence Erlbaum Associates, Mahwah, NJ, pp. 239–263.

Wickens, C. D. (2005), "Multiple Resource Time Sharing Model," in *Handbook of Human Factors and Ergonomics Methods*, N. A. Stanton, E. Salas, H. W. Hendrick, A. Hedge, and K. Brookhuis, Eds., Taylor & Francis, London, pp. 40-1–40-7.

Wickens, C. D. (2007), "Attention to Attention and Its Applications: A Concluding View," in *Attention: From Theory to Practice*, A. F. Kramer, D. A. Wiegmann, and A. Kirlik, Eds., Oxford University Press, Oxford.

Wickens, C. D. (2008), "Situation Awareness: Review of Mica Endsley's 1995 Articles on Situation Awareness Theory and Measurement," *Human Factors*, Vol. 50, No. 3, pp. 397–403.

Wickens, C. D. (2009), "Keynote Address: The Psychology of Aviation Surprise," in *Proceedings 15th International Symposium on Aviation Psychology*, P. Tsang and M. Vidulich, Eds., Wright State University, Dayton, OH.

Wickens, C. D., and Alexander, A. L. (2009), "Attentional Tunneling and Task Management in Synthetic Vision Displays," *International Journal of Aviation Psychology*, Vol. 19, pp. 182–189.

Wickens, C. D., and Andre, A. D. (1990), "Proximity Compatibility and Information Display: Effects of Color, Space, and Objectness on Information Integration," *Human Factors*, Vol. 32, pp. 61–77.

Wickens, C. D., and Carswell, C. M. (1995), "The Proximity Compatibility Principle: Its Psychological Foundation and Its Relevance to Display Design," *Human Factors*, Vol. 37, No. 3, pp. 473–494.

Wickens, C. D., and Hollands, J. (2000), *Engineering Psychology and Human Performance*, 3rd ed., Prentice-Hall, Upper Saddle River, NJ.

Wickens, C. D., and McCarley, J. M. (2008), *Applied Attention Theory*, CRC Press, Boca Raton, FL.

Wickens, C. D., and Prevett, T. (1995), "Exploring the Dimensions of Egocentricity in Aircraft Navigation Displays: Influences on Local Guidance and Global Situation Awareness," *Journal of Experimental Psychology: Applied*, Vol. 1, No. 2, pp. 110–135.

Wickens, C. D., Sandry, D., and Vidulich, M. (1983), "Compatibility and Resource Competition between Modalities of Input, Output, and Central Processing," *Human Factors*, Vol. 25, pp. 227–248.

Wickens, C. D., Vidulich, M., and Sandry-Garza, D. (1984), "Principles of S–C–R Compatibility with Spatial and Verbal Tasks: The Role of Display-Control Location and Voice-Interactive Display-Control Interfacing," *Human Factors*, Vol. 26, pp. 533–543.

Wickens, C. D., Zenyuh, J., Culp, V., and Marshak, W. (1985), "Voice and Manual Control in Dual Task Situations," in *Proceedings of the 29th Annual Meeting of the Human Factors Society*, Human Factors Society, Santa Monica, CA.

Wickens, C. D., Todd, S., and Seidler, K. S. (1989), "Three-Dimensional Displays: Perception, Implementation, and Applications," CSERIAC SOAR 89-001, Crew System Ergonomics Information Analysis Center, Wright-Patterson AFB, OH.

Wickens, C. D., Vincow, M. A., Schopper, A. W., and Lincoln, J. E. (1997), "Computational Models of Human Performance in the Design and Layout of Controls and Displays," CSERIAC SOAR 97-22, Crew System Ergonomics Information Analysis Center, Wright Patterson AFB, OH.

Wickens, C. D., Gempler, K., and Morphew, M. E. (2000), "Workload and Reliability of Predictor Displays in Aircraft Traffic Avoidance," *Transportation Human Factors Journal*, Vol. 2, No. 2, pp. 99–126.

Wickens, C. D., Goh, J., Helleberg, J., Horrey, W., and Talleur, D. A. (2003), "Attentional Models of Multitask Pilot Performance Using Advanced Display Technology," *Human Factors*, Vol. 45, No. 3, pp. 360–380.

Wickens, C. D., Ververs, P., and Fadden, S. (2004), "Head-Up Display Design," in *Human Factors for Civil Flight Deck Design*, D. Harris, Ed., Ashgate, Avebury, VT, pp. 103–140.

Wickens, C. D., Vincow, M., and Yeh, M. (2005), "Design Applications of Visual Spatial Thinking: The Importance of Frame of Reference," in *Handbook of Visual Spatial Thinking*, A. Miyaki and P. Shah, Eds., Oxford University Press, Oxford.

Wickens, C. D., McCarley, J. S., Alexander, A. L., Thomas, L. C., Ambinder, M., and Zheng, S. (2008), "Attention-Situation Awareness (A-SA) Model of Pilot Error," in *Human Performance Models in Aviation*, D. Foyle and B. Hooey (Eds.), Taylor & Francis, Boca Raton, FL.

Wickens, C. D. Hooey, B., Gore, B. F., Sebok, A, and Koenicke, C. (2009a), "Identifying Black Swans in NextGen: Predicting Human Performance in Off-Nominal Conditions," *Human Factors*, Vo. 51, pp. 638–651.

Wickens, C., Rice, S., Keller, M. D., Hutchins, S., Hughes. J., and Klayton, K. (2009b), "False Alerts in Air Traffic Control Conflict Alerting System: Is There A Cry Wolf Effect"? *Human Factors.*, Vol. 51, pp. 446–452.

Wickens, C. D., Keller, J., and Small, R. (2010),"Development of the Frame of Reference Transformation Tool (FORT)," in *Proceedings of the 54th Annual Meeting of the Human Factors and Ergonomics Society*, Human Factors Society, Santa Monica, CA.

Wickens, L. D., Alexander, A. L., Martens, M., and Ambinder, M. (2004), "The Role of Highlighting in Visual Search through Maps," *Spatial Vision*, Vol. 37, pp. 373–388.

Wickens, T. D. (2002), *Signal Detection Theory*, Freeman, San Francisco.

Wilkinson, R. T. (1964), "Artificial 'Signals' as an Aid to an Inspection Task," *Ergonomics*, Vol. 7, pp. 63–72.

Wolf, L. D., Potter, P., Sedge, J., Bosserman, S., Grayson, D., and Evanoff, B. (2006), "Describing Nurses' Work: Combining Quantitative and Qualitative Analysis," *Human Factors*, Vol. 48, pp. 5–14.

Wolfe, J. M. (2007), "Guided Search 2.0. A Revised Model of Visual Search," *Psychonomics Bulletin and Review*, Vol. 1, No. 2, pp. 202–238.

Wolfe, J. M., and Horowitz, T. S. (2004), "What Attributes Guide the Deployment of Visual Attention and How Do They Do It?" *Nature Neuroscience*, Vol. 5, pp. 1–7

Wolfe, J. M., Horowitz, T. S., and Kenner, N. M. (2005), "Rare Items Often Missed in Visual Searches," *Nature*, Vol. 435, pp. 439–440.

Woods, D., Wise, J., and Hanes, L. (1981), "An Evaluation of Nuclear Power Plant Safety Parameter Display Systems," in *Proceedings of the 25th Annual Meeting of the Human Factors Society*, Human Factors Society, Santa Monica, CA.

Woods, D. D., Johannesen, L. J., Cook, R. I., and Sarter, N. B. (1994), "Behind Human Error: Cognitive Systems, Computers, and Hindsight," CSERIAC #SOAR 94-01, Crew System Ergonomics Information Analysis Center, Wright-Patterson AFB, OH.

Yantis, S. (1993), "Stimulus Driven Attentional Capture," *Current Directions in Psychological Science*, Vol. 2, pp. 156–161.

Yates, J. F. (1990), *Judgment and Decision Making*, Prentice-Hall, Englewood Cliffs, NJ.

Yeh, M., and Wickens, C. D. (2001), "Attentional Filtering in the Design of Electronic Map Displays: A Comparison of Color-Coding, Intensity Coding, and Decluttering Techniques," *Human Factors*, Vol. 43, No. 4, pp. 543–562.

Yeh, M., Merlo J. L., Wickens, C. D., and Brandenburg, D. L. (2003), "Head Up Versus Head Down: The Costs of Imprecision, Unreliability, and Visual Clutter on Cue Effectiveness for Display Signaling," *Human Factors*, Vol. 45, No. 3, pp. 390–407.

Yntema, D. (1963), "Keeping Track of Several Things at Once," *Human Factors*, Vol. 6, pp. 7–17.

Yost, B., and North, C. (2006), "The Perceptual Scalability of Visualization," *IEEE Transactions on Visualization and Computer Graphics*, Vol. 12, No. 5, pp. 837–844.

Zheng, B., Janmohamed, Z., and MacKenzie, C. L. (2003), "Reaction Times and the Decision Making Process in Endoscopic Surgery," *Surgical Endoscopy*, Vol. 17, pp. 1475–1480.

Zsambok, C., and Klein, G. (1997), *Naturalistic Decision Making*, Lawrence Erlbaum Associates, Mahwah, NJ.