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# 6 Auditory Tasks in Cognitive Research

## INTRODUCTION

Basic and applied studies in cognition have generally used visual tasks to explore different aspects of human information processing. Nevertheless, although not as numerous, studies using nonverbal auditory tasks have also played an important role in investigations of perceptual and cognitive processing. Such tasks have ranged from simple clicks (to measure the brain stem evoked potential), to tones, musical patterns, environmental sounds, and rhythms. Neuroelectromagnetic responses to nonverbal sounds can be used to examine the integrity of central auditory pathways in infants and other nonverbal populations. Auditory detection tasks have been used to examine what has been termed the *psychological refractory period* (PRP) and as a secondary task index of mental workload. In fact, auditory tasks are frequently used to assess mental workload (Harms, 1986, 1991; Ullsperger, Freude, & Erdmann, 2001; Zeitlin, 1995); cognitive functioning, particularly after brain injury (Allen, Goldstein, & Aldarondo, 1999; Loring & Larrabee, 2006); and cognitive aging (Schneider & Pichora-Fuller, 2000).

These are only some examples of the many auditory tasks that have been used for more than a century to investigate attention, cognitive processing, and mental workload. As discussed in Chapter 4, the dichotic or selective listening task was a key technique in research on selective attention in the 1950s and 1960s, work that was highly influential in the beginning stages of the “cognitive revolution” (see Broadbent, 1958; C. Cherry, 1953b, 1957; Moray, 1959, 1969; Treisman, 1964a, 1960). Auditory tasks also played a key role in investigations leading to the development of early models of memory (see, e.g., Atkinson & Shiffrin, 1968; Broadbent, 1958; Waugh & Norman, 1965).

More recently, auditory tasks have been used in a variety of cognitive science investigations. Auditory tasks have been used to examine the nature of working memory (Baddeley, 1992; Cocchini, Logie, Della Sala, MacPherson, & Baddeley, 2002; Larsen & Baddeley, 2003); time perception (Brown & Boltz, 2002); age-related changes in cognitive functioning (Baldwin, 2001; Pichora-Fuller & Carson, 2001; Tun, 1998); and the neural mechanisms associated with learning and memory (Jones, Rothbart, & Posner, 2003; Posner & DiGirolamo, 2000). Auditory tasks are also frequently used to examine the mental workload associated with different operational environments, such as driving (Baldwin & Coyne, 2003; Baldwin & Schieber, 1995; Brown, 1965; Harms, 1986, 1991) and aviation (Coyne & Baldwin, 2003; Kramer, Sirevaag, & Braune, 1987; Wickens, Kramer, & Donchin, 1984).

In this chapter, the ways that auditory tasks have been used to investigate cognitive processing are examined, with a particular emphasis on investigations of mental workload. We discuss what these investigations demonstrate about the mental workload of auditory processing, as well as the need to consider the mental workload of auditory processing before reaching definitive conclusions regarding other aspects of cognitive functioning.

Auditory tasks that have been used in cognitive research differ in many ways, as the following examples illustrate. A great deal has been gained from these investigations, although all too frequently, researchers have neglected to consider the mental workload requirements of processing acoustic information. Factors such as individual differences in sensory capabilities challenge interpretation of many of these investigations. For example, as discussed extensively in Chapter 10, older adults with sensory impairments may require more mental effort during early sensory extraction processing stages, leaving a reduced supply of spare attentional effort to be used in the completion of subsequent stages of processing and additional tasks. Neglect of these basic issues, at least in some instances, calls into question the interpretation of the results obtained in these investigations and their implications for cognitive theories.

Another issue with many investigations in which auditory tasks have been used as a means to investigate cognitive processing is that incomplete information is provided on the actual acoustic characteristics of the presented stimuli. In terms of understanding implications for mental workload, particularly from the perspective of sensory-cognitive interaction theory (SCIT; Baldwin, 2002), it is most unfortunate that the presentation level (PL) used to present auditory materials is frequently not reported in the literature. In fact, in most published reports in which auditory issues are not the central focus, PLs are not reported. However, PL has been shown to affect the mental workload of processing speech tasks (Baldwin & Struckman-Johnson, 2002). When applicable, a discussion of the realized or potential impact of acoustic factors on the mental workload of auditory processing and the implications for strengthening understanding of the relevant cognitive mechanisms under investigation are discussed. First, we take a look at the role of auditory and verbal processing in historical developments within psychology.

## **HISTORICAL BEGINNINGS**

The study of auditory processing, and language processing in particular, has informed scientists of the workings of the human brain for centuries. In his book *The Story of Psychology*, Morton Hunt (1993) described the first psychological study as the effort of a seventh-century Egyptian king named Psamtik I (Figure 6.1) to use the innate language abilities of two feral children to discover the identity of the original human race. According to Hunt, the king reasoned that if the children were raised without any exposure to language, then their first words would be those of the first or original race. Unfortunately, the king apparently confused general babbling with actual words and came to the conclusion that the original race was not Egyptian as he had hoped. Nevertheless, as Hunt pointed out, the king's attempt to study the human mind empirically was remarkable for the time.



**FIGURE 6.1** Egyptian King Psamtik I.

According to Hunt (1993), verbal abilities were also the focus of Franz Josef Gall's (1758–1828) early interest in the brain and intellectual abilities. Gall purportedly observed, with annoyance, that some of his classmates in both grade school and college appeared to study less and yet achieve better grades. Gall reasoned that their superior performance in relation to their effort might be explained by more developed portions of the front part of their brain. “Evidence” for this came in Gall's observation that these individuals tended to have large, bulging eyes (no doubt being pushed out by the highly developed frontal brain areas). Gall's work in localizing mental functions, which came to be known as phrenology, was controversial largely due to his attempt to document intellectual differences between the races by correlating brain size with intelligence. Despite these spurious associations, Gall made significant contributions to scientific inquiries into the mind-brain relationship. Further, Gall's localization efforts included no less than four separate auditory-verbal areas. These included an area for (a) the memory of words; (b) the sense of language, speech; (c) the sense of sounds, the gift of music; and (d) poetic talent (see <http://www.phrenology.com/franzjosephgall.html>).

This “localizationist” perspective inspired Bouillaud's (1769–1881) search for the brain areas responsible for speech (see Kaitaro, 2001). Bouillaud's work described an understanding that the ability to use and produce speech are two different processes. This theme continued in the work of Paul Broca (1825–1880), who documented the characteristics, symptoms, and subsequent autopsy results from his famous aphasic patient, Leborgne, popularized in subsequent literature as “Tan” since he frequently repeated that utterance (Finger, 1994, pp. 37–38).

In his book *The Origins of Neuroscience: A History of Explorations into Brain Function*, Stanley Finger (1994) pointed out that the tremendous influence that Broca's documentation of the Leborgne case had on the scientific community was likely due to the culmination of several factors. First, not only was Broca highly respected, but



**FIGURE 6.2** Carl Wernicke.

also the time was right; it was a sort of tipping point or *zeitgeist*, as Finger called it. Whatever the reason, we see that Broca's documentation of Leborgne's language impairment marked the beginning of a new era in neuroscience.

Another example of the contributions of early auditory research in increasing knowledge of cognitive performance is found in the work of Carl Wernicke (1848–1905) (Figure 6.2). Wernicke is best known for his study of language impairments, or aphasias as they are commonly called. Wernicke documented several case studies of individuals with aphasic symptoms quite opposite those documented by Broca. Broca's account of aphasia involved individuals with an inability to produce speech despite a relatively intact ability to comprehend speech. Conversely, the cases examined by Wernicke included individuals with an inability to comprehend speech. These individuals were able to speak words fluently, although the resulting speech lacked conceptual coherence (Finger, 1994).

Wernicke's observations provided converging evidence for the localization of language function and the existence of separate processes for producing and comprehending speech. Less well known are Wernicke's writings considering the nature of conceptual knowledge. Wernicke believed that language and thought were separate processes (Gage & Hickok, 2005). Therefore, even in his earliest writings he was compelled to discuss the nature of conceptual representations in addition to language representations. As Gage and Hickok discussed, Wernicke's theories regarding cortical mechanisms involved in the representation of conceptual knowledge are strikingly similar to modern accounts by notable cognitive neuroscientists such as Squire (1986) and Damasio (1989). Similar themes appeared in an article by Jonides et al. (2005). The basic similarities between Wernicke's writing over a century ago and more recent publications include the idea that memories are represented in the

same neural pathways initially used to encode the stimulus information. For example, processing and storing speech would utilize a broadly distributed set of neural pathways, including the auditory pathways activated by the auditory stimulus. Associations between auditory and visual concepts arise “coincidentally” when two sets of neural pathways are activated at the same time. Future activation of part of one of the pathways is sufficient to activate the entire neural trace in both modalities (see discussion in Gage & Hickok, 2005).

Wernicke’s theories of conceptual neural representations seem far advanced for his time. Modern neuroscience techniques currently enable investigators to examine their plausibility. Since we are awaiting further research in these areas, we return to more pedestrian examples of the use of auditory tasks in cognitive research. We begin with an extension of the discussion of dichotic listening tasks from Chapter 4, citing recent applications that have furthered our knowledge of attention. This is followed by a discussion of a variety of auditory tasks that have been used as indices of mental workload. Included in this discussion is a review of common auditorily administered neurophysiological indices and neuropsychological tests designed to assess cortical processing and impairment. The focus here is not to present an exhaustive discussion of the many ways auditory tasks have been used but rather to provide sufficient support for the argument that they have played an integral role in human performance research, past and present. We begin by revisiting the topic of dichotic listening tasks introduced in Chapter 4.

## DICHOTIC LISTENING TASKS

Dichotic listening tasks were originally primarily used to examine the nature of selective attention and its role in information processing. More recently, dichotic listening tasks have been used as a measure of cerebral dominance (Rahman, Cockburn, & Govier, 2008); as an index of attentional control (Andersson, Reinvang, Wehling, Hugdahl, & Lundervold, 2008); for examination of new theories of anticipatory and reactive attending (Jones, Johnston, & Puente, 2006; Jones, Moynihan, MacKenzie, & Puente, 2002); and as neuropsychological tests of attention capabilities in individuals suspected to exhibit attentional deficits (Diamond, 2005; Hale, Zaidel, McGough, Phillips, & McCracken, 2006; Shinn, Baran, Moncrieff, & Musiek, 2005).

Considerable empirical evidence indicates that mental effort is required to attend selectively to one auditory message in the presence of competing auditory stimuli (Moray, 1969; Ninio & Kahneman, 1974). The selective listening paradigm was used extensively to investigate attentional functioning during the 1950s and 1960s. The dichotic listening paradigm, in which separate auditory messages are presented to each of the two ears (C. Cherry, 1953a; Moray, 1959; Treisman, 1960, 1964b), was most common. More recently, dichotic listening tasks have been used to examine new theories of anticipatory and reactive attending (Jones et al., 2002, 2006) and as neuropsychological tests of attention capabilities in individuals suspected to exhibit attentional deficits.

In the typical dichotic listening task, listeners are asked to “shadow” or repeat aloud one of the two messages. Following presentation of the messages, listeners would generally be asked to recall the semantic content of the messages, to identify or answer content-related questions (Moray, 1969). Moray pointed out that selective

listening tasks are commonly found in many real-world tasks, such as in the air traffic control (ATC) tower, where the ATC operator must selectively attend to one of several simultaneous messages. Similar tasks are also found in classrooms, offices, dispatch headquarters, and medical emergency rooms, to name a few. In the laboratory, another version of the dichotic listening task asks listeners to attend selectively to one of two or more messages and make responses according to some criterion, such as the presence of a word from a particular category (Kahneman, Ben-Ishai, & Lotan, 1973; Ninio & Kahneman, 1974).

A number of generalizations can be made from these investigations (Moray, 1969). The more similar the two messages are, the harder it will be to attend selectively to only one. Messages are more easily separable if they involve distinctly different loudness levels or pitch, if they arrive from distinctly different physical locations (including different ears such as in the dichotic listening paradigm), or even when location is perceptually but not physically different due to experimental manipulations of timing and intensity (Li, Daneman, Qi, & Schneider, 2004). Messages are also more easily separated if the gender of the speakers is different (Egan, Carterette, & Thwing, 1954; Treisman, 1964b).

Moray pointed out that using dichotic presentation to separate two messages (versus monaural presentation) is equivalent to increasing the signal-to-noise ratio (S/N) of the selected message by as much as 30 dB (Egan et al., 1954; Moray, 1969). Egan and colleagues used the articulation score (or the accuracy with which a message could be identified) as the dependent variable. Egan found that when two messages were spoken by the same speaker, were started at the same time, and were presented at the same intensity, the articulation score was 50%. However, using a high-pass filter on either the selected or unselected message improved selective listening, resulting in an articulation score of roughly 70% if the selected message was high-pass filtered and roughly 90% when the rejected message was filtered. These results suggest that greater interference will result when the competing message is similar to the attended message. It is easier to ignore a competing message if it is physically different from the attended message. This finding is important to consider when designing auditory messages in operational environments. As an illustration, in the flight cockpit, where male voices have been traditionally more prevalent, verbal warnings and messages presented in a female voice will be more salient.

## ENCODING AND RETRIEVAL PROCESSES

An extensive body of literature now exists on the nature of encoding and retrieval of information in memory. Many of these investigations have utilized aurally presented word tasks (Craig, Govoni, Naveh-Benjamin, & Anderson, 1996). For example, Fergus Craig and colleagues (1996) examined the effects of divided attention during encoding and retrieval of aurally presented words. Their dual-task paradigm indicated that divided attention during the encoding of words significantly disrupted memory for those words, while divided attention during the retrieval of words increased the time needed to respond to a visual reaction time task.

In general, a concurrent task is more disruptive when people are trying to encode speech for later recall, rather than when the concurrent task occurs during retrieval

(Anderson et al., 1998; Naveh-Benjamin, Craik, Guez, & Dori, 1998). Both young and old participants experienced greater dual-task costs during auditory encoding; however, the effects were particularly dramatic for older listeners (Anderson et al., 1998). Interestingly, using the same voice to present words during both encoding and retrieval resulted in significantly better recall of words (Naveh-Benjamin et al., 1998) than using a different voice during retrieval.

The memory enhancement effects of presenting to-be-remembered items in the same voice during encoding and recall exemplifies the multiple memory trace models of speech comprehension. Several models of speech comprehension proposed that parallel memory traces are temporarily stored during speech processing (Ju & Luce, 2006; Luce, Goldinger, Auer, & Vitevitch, 2000; Wingfield & Tun, 1999). The redundant memory traces stemming from acoustic-phonological representation in conjunction with semantic-conceptual representations could be expected to improve memory.

## AUDITORY TASK INDICES OF WORKING MEMORY

Working memory is commonly conceptualized as a short-term store for temporarily working with or manipulating information (Baddeley, 1992; Baddeley & Hitch, 1974). The term has essentially replaced the concept of short-term memory in much of the cognitive literature (Lobley, Baddeley, & Gathercole, 2005; Wingfield & Tun, 1999). We discussed the role of working memory in Chapter 4 but return to it in this chapter and focus particularly on some of the many auditory tasks that have been used in investigations of working memory processes. We begin with an extremely influential study that sparked much theoretical discussion and that continues to be the focus of much debate: Daneman and Carpenter's (1980) investigation of listening and reading span.

### WORKING MEMORY CAPACITY: COMPLEX SPAN

Daneman and Carpenter published a seminal article in 1980 that addressed the role of individual differences in listening and reading abilities. It was commonly believed at the time that short-term memory must play a role in language comprehension, yet measures of short-term memory capacity (i.e., word span and digit span) appeared to share little relationship with measures of reading and listening comprehension (Daneman & Carpenter, 1980; Daneman & Merikle, 1996). Daneman and Carpenter's paradigm, which they termed the reading span and listening span task, required both processing and storage of verbal information. Rather than simply requiring participants to attempt to recall a string of unrelated words or digits (as in the word span and digit span tasks), the reading or listening span task requires people to process a series of sentences (presented either visually in the case of the reading span or aurally in the case of the listening span) and make a veracity judgment of each sentence while attempting to store the last word from each sentence. Originally, Daneman and Carpenter (1980) had people read a series of unrelated sentences at their own pace and then recall the final word from each sentence.

More recently, the reading span test has been modified somewhat following the example of Engle and colleagues (la Pointe & Engle, 1990; Unsworth & Engle, 2006). In their version, people are required to verify whether a sentence is grammatical or

not and then to remember a stimulus item presented immediately after sentence verification. For example, a listener might read a sentence such as: “The senator was glad for the term recess so he could resume his watermelon ties,” to which the listener should respond “No” because the sentence does not make grammatical sense. Then, an unrelated stimulus item such as “Yes” is presented for later recall.

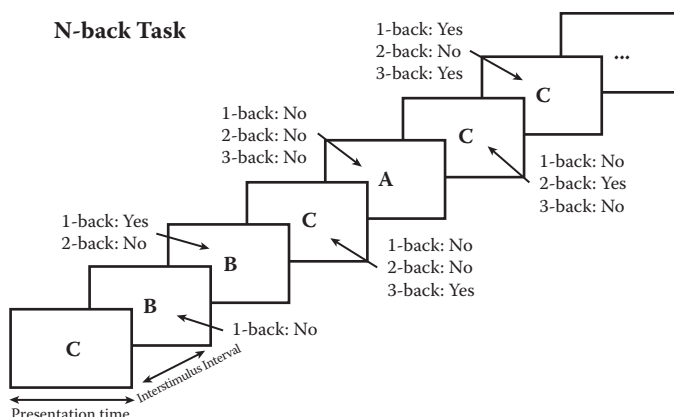
Daneman and Carpenter’s (1980) reading span and listening span task proved to be much more predictive of language comprehension abilities than digit or word span tasks. Numerous subsequent investigations have confirmed these observations (see a meta-analytical review in Daneman & Merikle, 1996).

## LISTENING SPAN

Several investigations have implemented the listening span task in a variety of unique and productive ways. First, as Daneman and Carpenter (1980) originally intended, several investigators utilized the listening span task to examine individual differences in language comprehension in school-age children. For example, listening span tasks are often predictive of reading ability (Swanson & Howell, 2001) and the incidence and severity of learning disabilities (Henry, 2001) in school-age children.

The listening span task may also be predictive of the ability of children of school age to attend to and comprehend academic lessons on a daily basis. Morria and Sarll (2001) examined listening span performance of A-level students in the morning after they had skipped breakfast. Their performance was then compared again after consuming either a glucose drink or a placebo, saccharine-sweetened drink. Twenty minutes after consuming the drink, students who had drunk glucose relative to placebo performed significantly better on the listening span task. Performance in this glucose group improved despite nonsignificant changes in their blood sugar levels. Performance in the placebo group remained unchanged. Results of this investigation underscore the importance of children receiving adequate nutrition and breakfast, in particular (Benton & Jarvis, 2007; Muthayya et al., 2007). The cognitive benefits obtained from eating breakfast can be enhanced in school-age children by also including a midmorning snack, and these benefits are most dramatic for children of low socioeconomic status and those nutritionally at risk (Pollitt, 1995). The impact of morning nutrition on cognitive performance is not limited to children. Young college-age adults showed similar cognitive changes and have demonstrated significantly increased verbal reasoning skills following frequent small meals versus skipping meals altogether or consuming less-frequent larger meals (Hewlett, Smith, & Lucas, 2009). Performance on listening span tasks is also affected by PL, indicating that it is important to evaluate the mental effort involved in carrying out such tasks.

The importance of considering the mental workload of the auditory processing task when assessing listening span can be seen in an investigation of the influence of speech PL (how loudly the speech was presented) on performance (Baldwin & Ash, 2010). A direct intensity relationship was found between presentation intensity and working memory capacity. As intensity increased, assessed listening span capacity also increased. This direct relationship was particularly evident in a group of older (60–80 years), relative to young (18–31 years), listeners.



**FIGURE 6.3** The *n*-back task.

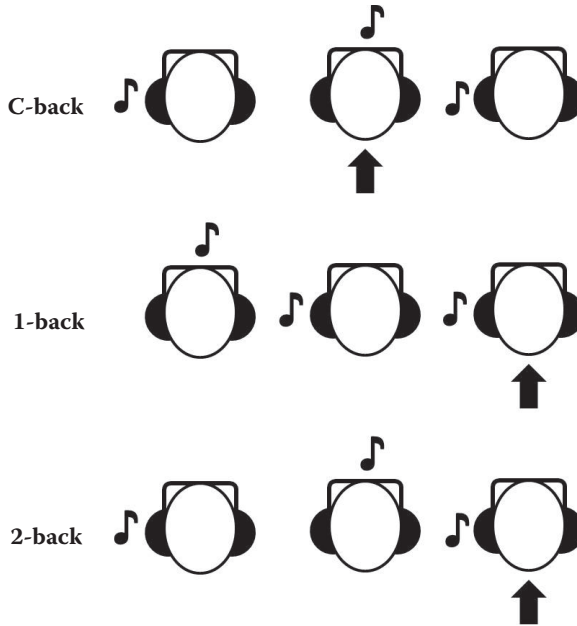
### AUDITORY *N*-BACK TASKS

Another commonly used task that is often presented in the auditory modality is the *n*-back task. The *n*-back task is commonly used to investigate various aspects of working memory. As illustrated in Figure 6.3, participants are asked to monitor an incoming stream of stimuli and make some response (such as indicating the presence or absence of a match to the current stimulus) to items *n* trials previously in the stream. For instance, in a 2-back task, participants are required to make some decision and response in conjunction with the stimulus presented 2 positions back. The difficulty of the task can be manipulated by varying the target position, with the easiest version being the 1-back task (where responses are made to the immediately preceding stimulus) and more difficult versions requiring responses to trials with more intervening stimuli.

Several versions of the *n*-back task have been developed and utilized. Stimuli may be verbal or nonverbal, and people may be asked to monitor either the identity or the location of the stimuli (Owen, McMillan, Laird, & Bullmore, 2005).

Figure 6.4 illustrates a version of the auditory-spatial *n*-back task. Note that by manipulating interaural intensity differences the letters presented seem to come from the left side, the right side, or the middle of the head. Researchers at the University of Helsinki in Finland have been using an auditory-spatial version of the *n*-back task such as the one illustrated in Figure 6.4 to investigate working memory in school-age children (Steenari et al., 2003; Vuontela et al., 2003). Using headphones, they achieved the perception that stimuli were coming from one direction or the other by using interaural intensity differences of approximately 17 dB. For example, to present stimuli that appear to be coming from the left, the left ear sound is presented 17 dB louder than that presented simultaneously to the right ear and vice versa for the simulated right position. Sounds of equal intensity appeared to come from the middle.

This auditory-spatial version of the *n*-back task has been used to examine the effects of sleep quantity and quality on school-age children (Steenari et al., 2003). Steenari and colleagues observed that poorer sleep quality (more activity during sleep as measured by an actigraph) was associated with poorer working memory performance at



**FIGURE 6.4** Auditory-spatial  $n$ -back task.

all task load levels. Shorter sleep durations were associated with poorer performance on the most difficult version (2-back) of the auditory-spatial task. They concluded that working memory in school age-children was related to both sleep quality and duration.

Using the same version of the auditory-spatial  $n$ -back task, Vuontela and colleagues (2003) observed that working memory performance improved across the age range of 6 to 13 years. They interpreted this as evidence for the maturation of cognitive mechanisms across this time frame. They also noted that working memory appeared to develop slightly faster in females, at least to age 10 years. Further, they noted that auditory-spatial working memory seems to mature more slowly than its visual counterpart.

Despite the reliance on speeded sensory-perceptual processing in these working memory tasks, all too frequently little if any care is taken to ensure that participants have been equated for sensory acuity. As previously discussed, recent work in our lab indicated that both sensory acuity and stimulus presentation characteristics affected listening span indices of complex span (Baldwin & Ash, in preparation). We return to a discussion of this issue later in this chapter. Now, we turn to another paradigm that has made considerable use of auditory tasks.

## PSYCHOLOGICAL REFRACTORY PERIOD

The use of auditory tasks in dual-task studies often involves a phenomenon referred to as the psychological refractory period (PRP). The PRP paradigm requires people to make speeded responses to stimuli from two different tasks in rapid succession

(see review in Pashler, 1998a; Welford, 1952). It is generally found that people take longer to respond to the second task when it follows the first task closely in time. Pashler (1998b) gave a helpful analogy to explain the predictions of the PRP paradigm with respect to processing bottlenecks. His analogy involved two people going into a bank, one right after the other. If the two people arrive at almost the same time and it takes the same amount of time for each person to get their banking done as it would have if they had arrived by themselves, then we could say that they accomplished the respective tasks in parallel. If, however, it takes longer for the person who arrives second, then there must be a bottleneck in the process. For example, the bottleneck might be the teller. The second person may need to wait for the first to finish with the teller. In this case, the first person would finish in the same amount of time, but the second one would take longer to accomplish the banking task.

Results of numerous investigations using the PRP paradigm have provided support for a central bottleneck theory of informational processing (Levy & Pashler, 2008; Levy, Pashler, & Boer, 2006; Pashler, 1998b). For example, using a visually presented memory task involving word pairs in conjunction with an auditory tone discrimination task, Pashler observed that memory retrieval was delayed when cue stimuli were presented in close temporal proximity to the auditory task stimuli (Carrier & Pashler, 1995). Results of this auditory-visual task paradigm indicated that retrieving items from memory is subject to a central processing bottleneck. That is, processing auditory stimuli from one task interfered with memory retrieval in a separate task, indicating that both tasks were relying on some shared mechanism and could not therefore be processed in parallel.

In a more recent investigation, Levy, Pashler, and colleagues (Levy & Pashler, 2008; Levy et al., 2006) investigated this relationship in the context of simulated driving while participants performed a concurrent task. It is well known that drivers often engage in a number of extraneous tasks while driving. Researchers sought to see how auditory processing might have an impact on brake response time. In one experiment, participants were asked to make speeded brake responses in a simulated driving task concurrently with a visual or auditory choice response task. Stimulus onset asynchrony (SOA), or the time between presentation of the stimuli from the two tasks, significantly affected brake response times. When the auditory or visual task stimuli were presented in close temporal proximity to the visual stimuli in the brake response task, participants took significantly longer to perform the brake response. The practical implications of this study for driving and performing other extraneous tasks concurrently are important. It appears that performing a visual or auditory task just prior to a brake event will slow response time.

In a subsequent study, Levy and Pashler (2008) used the change-task design in which two tasks are presented, but participants are told to prioritize them such that they are to stop processing and responding to the first task if the second task is presented. For example, as Levy and Pashler pointed out, a person might be performing the low-priority task of listening to the radio while driving, but if a lead car suddenly brakes in front of him or her, attention should be taken away from the listening task and devoted to the task of applying the brakes. People seemed to be able to withhold processing of and thus response to the first task some of the time but not consistently (Logan & Burkell, 1986). Levy and Pashler combined a choice auditory tone task

(Task 1 of low priority) with a brake response time task (high-priority Task 2). First, they observed substantial individual differences in people's ability to withhold making a response to the low-priority auditory tone task during the presence of a lead car braking event (the signal to perform the Task 2 brake responses) despite explicit instructions that the brake response task was to take priority over the tone task. The majority of participants (60%) failed to withhold the tone response over 80% of the time, while two other groups of moderate response rate (40–80% of the time) and low response (under 40%) each represented 20% of the sample. Clearly, people had a difficult time disengaging from the auditory tone-processing task and withholding their response. Levy and Pashler took this as evidence for a central processing bottleneck.

Second, Levy and Pashler (2008) observed that mistakenly performing the auditory task first significantly slowed brake response time. This effect is perhaps not surprising but has important practical implications. It suggests that even when people are clearly aware of the higher priority of a given task, they may be unable to stop themselves from completing a task of lower priority. This failure to inhibit attention toward lower-priority tasks affects their ability to perform a high-priority task. Consider when a driver engaged in a cell phone conversation takes the time to tell the caller that he or she has to end the call rather than just dropping the phone during a critical event. Perhaps the driver may even take the time to explain to the caller why he or she has to hang up. Evidence is clear that performance decrements occur whenever people attempt to perform two different tasks within close temporal succession, although the mechanisms behind this interference continue to be debated (Jentzsch, Leuthold, & Ulrich, 2007; Navon & Miller, 2002; Pashler, Harris, & Nuechterlein, 2008; Schubert, Fischer, & Stelzel, 2008).

Next, we examine the use of auditory tasks in dual-task paradigms for a different purpose: assessing the mental workload associated with performing a task or using a system. In these cases, the auditory task may be called a secondary task or subsidiary task, and performance measures of response time and accuracy are usually assessed. Other investigations aimed at assessing mental workload have used auditory evoked potentials or event-related potentials (ERPs) in response to auditory stimuli. We turn now to a discussion of some of the commonly used auditory tasks in mental workload research.

## MENTAL WORKLOAD ASSESSMENT

Mental workload assessment, as described in some detail in Chapter 5, has played an integral role in investigations of human performance. Auditory tasks have frequently been used in these investigations, often because the task or system of interest (i.e., driving or piloting) already placed heavy demands on visual processing channels. In this section, we discuss some of the commonly used auditory secondary tasks and auditory ERP tasks that have been employed in mental workload assessment.

### AUDITORY SECONDARY TASKS

Tasks such as logical sentence verification, mental arithmetic, and delayed digit recall, in which the stimuli are presented acoustically, can and have been used as

secondary tasks to investigate workload in a wide variety of environments. Auditory secondary tasks have been used to examine new cockpit displays and for examining the affect of environmental factors (such as the difficulty of driving through complex roadways of varying levels of traffic density) on mental workload during driving. For example, a secondary task consisting of auditory mental arithmetic has been found to be sensitive to the mental workload requirements of driving in urban versus rural settings (Harms, 1991). Delayed recall of acoustically presented digits was found to be a sensitive index of changes in mental workload stemming from changes in traffic density and adverse weather (Zeitlin, 1995).

### **Delayed Digit Recall**

The delayed digit recall task has a long history of use, introduced as early as 1959 by Jane Mackworth (1959). It is similar to the *n*-back task described previously; however, in the delayed digit recall, task digits from 1 to 9 are presented in a random sequence at specific intervals. Participants are then required to say aloud a previously presented digit (Zeitlin, 1995). As with the *n*-back task, the difficulty of the delayed recall task can be manipulated through specifications of the digit to be recalled. For example, in the easiest condition the participant would simply be required to repeat the last digit presented. A more complex version of the task requires participants to repeat digits presented earlier in the sequence (i.e., two digits before the last digit spoken) or to repeat digits that followed a specified target digit (i.e., the second digit following the last presentation of the number 3 in the sequence).

The delayed digit recall task has been shown to be sensitive to changes in the driving environment in a 4-year investigation of the mental workload of commuters in the New York City area (Zeitlin, 1995). Zeitlin's implementation used a presentation rate of one digit every 2 s for a period of 2 min. Participants were required to say the digit preceding the last digit presented and were required to reach a performance criterion of 98% accuracy in a no-load condition prior to participating in the experimental trials.

### **Mental Arithmetic**

Mental arithmetic tasks have been used extensively as secondary task measures of mental workload. In both laboratory environments (Garvey & Knowles, 1954) and field investigations (Harms, 1991), mental arithmetic tasks have been sensitive to changes in the difficulty of the primary task without disrupting primary task performance. By using auditory inputs for the arithmetic task in combination with spoken responses, there is little chance of direct interference with most visual/motor tasks (Knowles, 1963), making them well suited for a number of operator tasks, such as piloting and driving.

The difficulty of the mental arithmetic task can be varied in many ways. In one version used by Kahneman and colleagues (1969), a prompt, "ready," preceded presentation of three randomized digits. Listeners were instructed to keep each of the digits in memory until a second prompt, "now," was heard. On hearing "now," listeners were asked to add 3 to each of the three preceding digits and verbally report the transformed calculation in order. In one investigation designed specifically to examine the sensitivity and intrusiveness of different workload assessment techniques, the

version of the mental arithmetic task modeled after the one previously implemented by Kahneman was not found to be sensitive to changes in flight simulator difficulty manipulated by increasing wind gust disturbance (Wierwille & Connor, 1983). Wierwille and Connor estimated that a sample size of at least 25 participants would be needed for that form of mental arithmetic task to indicate statistically significant sensitivity to the primary flight task difficulty. However, other investigations using a different form of mental arithmetic task have demonstrated sensitivity to primary task difficulty with fewer participants (Baldwin & Schieber, 1995; Harms, 1991).

Baldwin and Schieber (1995) and Harms (1991) have used a version of mental arithmetic in which two-digit numbers are presented and listeners are required to subtract the smaller from the larger of the set (i.e., if “57” is presented, listeners should subtract the 5 from the 7 and verbally report the result, “2”). This subtraction version has been found to be sensitive to changes in primary task driving difficulty in both driving simulation (Baldwin & Schieber, 1995) and on-the-road investigations of driving (Harms, 1991).

Auditory versions of the *n*-back task discussed in this chapter, as well as a wide range of other tasks presented in the auditory modality, have been used in mental workload assessment (see review in Ogden et al., 1979). A specific class of these tasks, those used in conjunction with ERP techniques, is discussed next.

## AUDITORY ERP INDICES OF MENTAL WORKLOAD

Auditory ERP paradigms have been developed to examine mental workload in a number of occupational environments. In particular, the P300 component, a positive wave deflection occurring approximately 300 ms after an infrequent or unexpected stimulus event, is frequently found to be sensitive to the attentional processing requirements of a given task or task set. The P300 is said to be an endogenous component reflecting attentional processing. During divided attention tasks, a decrease in the P300 component in response to a secondary task event has been found to be indicative of greater attentional costs associated with a primary task. In other words, as the primary task becomes more mentally demanding, fewer resources are available for processing the secondary task, and this is demonstrated by a P300 of decreased amplitude to the secondary task event (Kramer et al., 1987). Based on this relationship, a technique called the auditory oddball paradigm, which is discussed in the next section, has been used extensively as a physiological index of mental workload.

### Auditory Oddball Paradigm

The auditory oddball paradigm capitalizes on the observation that humans are geared to devoting attentional resources to novel stimuli. Novel stimuli can be said to capture attention and therefore result in the utilization of mental resources for processing. In the auditory oddball paradigm, a series of tones is presented. The listener is instructed to ignore all but a distinct target tone, which is presented periodically but considerably less frequently than the standard or distractor tones. For example, the distractor tone may be presented 80% of the time, with the target tone presented in only 20% of the targets. Typically, target tones illicit a P300 component of relatively greater amplitude than is observed for the distractor tones. The observed increased

amplitude to the novel stimuli is interpreted as demonstrating that the target tone is being processed. However, as more attentional resources are required by a concurrent task, the relative increase in P300 amplitude to the target tones relative to the distractor tones diminishes. Kramer and colleagues (1987) demonstrated the effectiveness of the auditory oddball paradigm to distinguish between levels of operator workload during simulated flight missions. Specifically, they found that P300 amplitude decreased with increases in flight task difficulty manipulated through wind turbulence and segment (e.g., taking off and landing vs. level flight).

The auditory P300 has also been used in the evaluation of the difficulty of text presented in hypermedia systems (Schultheis & Jameson, 2004). Schultheis and Jameson paired an auditory oddball task with easy and difficult versions of text and measured pupil diameter and the P300 response to the oddball task. P300 amplitude, but not pupil diameter, was significantly reduced for the difficult hypermedia condition. The authors concluded that auditory P300 amplitude and other measures, such as reading speed, may be combined to evaluate the relative ease of use of different hypermedia systems and perhaps even to adaptively vary text difficulty dependent on the cognitive workload experienced by the user.

In another example of the use of the auditory P300, Baldwin and Coyne (2005) found that P300 amplitude was sensitive to the increased difficulty of driving in poor visibility due to fog versus clear visibility, while performance-based and subjective indices were not. They developed analogous auditory and visual versions of the P300 task that could be used to compare displays of different modalities without overtaxing the primary task sensory modality. However, using a cross-modal oddball task did not demonstrate adequate sensitivity in several flight and driving simulation investigations; therefore, caution must be exercised in making recommendations for this procedure. Another auditory version of an ERP task that has been used successfully to assess mental workload is the irrelevant probe task.

### **Irrelevant Probe Task**

In the auditory irrelevant probe task, people are asked to ignore a periodic auditory probe. The probe is thus irrelevant to the task the person is performing. However, ERP responses to these irrelevant probes can sometimes be used effectively as indices of mental workload. For example, the N1 component in response to an auditory irrelevant probe task was sensitive to more difficult sections of a flight task (Kramer et al., 1987). The benefit of the irrelevant probe task compared to many others is that it does not require the operator to perform any other tasks.

These examples clearly point to the utility of the auditory tasks in conjunction with ERP techniques in assessing cognitive workload in a wide variety of domains. The auditory oddball task has also been used in neuropsychological assessment of cognitive status, as discussed next.

## **AUDITORY NEUROPSYCHOLOGICAL TESTS**

Auditory tasks are frequently used in neuropsychological examinations (Sjogren, Christrup, Petersen, & Hojsted, 2005; Tombaugh, 2006; White, Hutchens, & Lubar, 2005). For example, the Paced Auditory Serial Addition Task (PASAT) is a common

neuropsychological test of information processing and working memory, and auditory verbal learning tests (AVLTs), such as the Rey Auditory Verbal Learning Test, are frequently used to assess cognitive function. Several neuropsychological assessment batteries contain one or more auditory or verbal components. For example, of the 10 subtests of the Halstead-Reitan Neuropsychological Test Battery (HRNTB), one (the Rhythm test) relies on auditory processing of pairs of nonverbal sounds. A second subtest requires recognition of auditorily presented nonsense words.

### **PACED AUDITORY SERIAL ADDITION TASK**

The PASAT was originally developed as a tool for assessing cognitive function and information processing speed in particular, following traumatic brain injury (for a review, see Tombaugh, 2006). It involves presenting a series of single-digit numbers and having the patient or participant sum each two consecutive numbers, reporting aloud the answers. So, for example, if 5, 7, 3, and 9 were presented, the correct verbal responses would be 12, 10, and 12. As discussed in a review by Tombaugh (2006), the PASAT is a commonly used neuropsychological test of attention, but it has been found to be affected by such factors as age and speech and language abilities. As discussed in detail in Chapter 10, age-related changes in cognitive performance void of careful assessment of sensory acuity must be regarded with extreme caution. Degradations in performance associated with age could be attributed to peripheral or central hearing mechanisms rather than cognitive deficits. As suggested by SCIT (Baldwin, 2002) and the effortfulness hypothesis (McCoy et al., 2005; Wingfield, Tun, & McCoy, 2005), the additional mental effort required to process degraded sensory stimuli may deplete resources from other, later stages of processing. In this way, declining sensory abilities could exacerbate or be mistaken for cognitive impairments (Baldwin, 2002; Baldwin & Ash, 2010; Baldwin & Struckman-Johnson, 2002; Valentijn et al., 2005).

Clinical evidence for the importance of assessing auditory acuity in AVLTs comes from work conducted in conjunction with the Maastricht Aging Study (van Boxtel et al., 2000). Using an auditory verbal learning paradigm and controlling for factors such as age, educational level, and speed of processing, van Boxtel and colleagues observed that hearing acuity was a strong predictor of performance on auditorily administered verbal learning tests.

An additional caveat is that performance on the PASAT often varies considerably depending on the modality of stimulus presentation. As might be predicted from a multiple-resource theory perspective (Wickens, 1984), recent evidence indicated that people may score substantially better when the test is administered in visual rather than auditory format (Wickens, 1984). This discrepancy in performance obtained with a visual versus an aural presentation modality suggests that resource competition between mechanisms responsible for encoding the auditory information and making a verbal response may be at least in part what the PASAT is assessing. This would suggest the PASAT may be assessing the ability to switch auditory attention rapidly rather than merely assessing information-processing speed alone.

For example, the PASAT has been used to examine the impact of pharmaceuticals, such as opioids, on cognitive function in patient populations experiencing

chronic pain (Sjogren et al., 2005). The PASAT has also been used as a means of examining working memory processing in clinical populations with attention deficit/hyperactivity disorder (ADHD) (White et al., 2005).

### **REY AUDITORY VERBAL LEARNING TEST**

The Rey Auditory Verbal Learning Test (RAVLT) is one of the most commonly used AVLTs for neuropsychological assessment (Baños, Elliott, & Schmitt, 2005; Poreh, 2005). The RAVLT is also one of the oldest, and its list-learning format has formed the basis for subsequent AVLTs, such as the California Verbal Learning Test, the Wechsler Memory Scale (WMS-III), and the Hopkins Verbal Learning Test. It consists of reading aloud a list of 15 words (List A), asking for free recall, and then presenting the same list four more times with a free recall trial between each. Then, a second list (List B) is presented, followed by free recall. People are then asked to recall List A without it being presented again. In this way, the first recall trial of List A is similar to other immediate memory tests, such as the digit span task. List B is a form of interference. The RAVLT is easy to administer, taking on the order of 10–15 min.

### **HALSTEAD-REITAN NEUROPSYCHOLOGICAL TEST BATTERY**

The HRNTB is commonly used to assess and diagnose neurological impairment due to factors such as brain trauma, mental disorder, and alcoholism (Allen et al., 1999; Horton, 2000; Sweeney, 1999). It consists of several tests and makes use of visual, auditory, and tactile presentation modalities (Reitan & Wolfson, 2000, 2005). The two auditory tests include the Speech-Sounds Reception Test (SSRT) and the Seashore Rhythm Test.

#### **Speech-Sounds Reception Test**

The speech-sounds reception test involves auditorily presenting prerecorded nonsense words that rhyme with the “ee” sound. Listeners are required to identify the corresponding letter representations from a set of nonsense words. The test is similar to the Speech Perception in Noise (SPIN) test (Plomp & Mimpen, 1979) and its revised version R-SPIN, except that SPIN tests present the speech sounds in carrier sentences along with varying levels of noise.

#### **Seashore Rhythm Test**

The Seashore test was originally part of Carl Seashore’s 1939 Measures of Musical Talent test that was administered in an effort to discover musical prodigies. The Seashore Rhythm Test is now included in the HRNTB and consists of discriminating between rhythmic patterns of beats. The modified Seashore Rhythm Test is frequently used as an index of neurological impairment and attentional processing abilities. Taylor-Cooke and Fastenau (2004), for instance, found that the Seashore Rhythm Test distinguished attentional processing deficits in children with epilepsy relative to controls. However, the clinical validity of the Seashore test is sometimes questioned (see review in Sherer, Parsons, Nixon, & Adams, 1991).

There are numerous other auditory tasks that have been used for neuropsychological assessment. But, the list of tasks described in this section should serve to provide an adequate account for the present purposes. We now change to a focus on auditory tasks that have been used in neurophysiological investigations.

## NEUROPHYSIOLOGICAL INVESTIGATIONS

As in other arenas, a variety of auditory tasks has been used in neurophysiological investigations of perceptual and cognitive processing. These tasks have ranged from simple auditory clicks that measure brain stem response, to tones, musical patterns, rhythms, words, and sentences.

### PREPULSE INHIBITION

Prepulse inhibition (PPI) refers to a reduction in the startle response to a strong sensory stimulus when the stimulus is preceded by a weaker stimulus (Filion & Poje, 2003; Schall & Ward, 1996). Frances Graham (1975) proposed that the PPI might be used as a measure of central processing level. Since that time, PPI has demonstrated sensitivity to a number of clinical pathologies, including schizophrenia and autism.

PPI is a sensitive index of central inhibitory mechanisms or sensorimotor gating (Grillon, Ameli, Charney, Krystal, & Braff, 1992; Perry, Geyer, & Braff, 1999) and central serotonergic functioning (Quednow, Kuhn, Hoenig, Maier, & Wagner, 2004). Generally, patients with schizophrenia demonstrate reduced PPI (Grillon et al., 1992; Kumari, Aasen, & Sharma, 2004; Perry et al., 1999), although Kumari et al. (2004) found that the PPI of female patients with schizophrenia did not differ from normal female controls. Schizophrenia aside, PPI shows consistent sex differences, with females exhibiting lower PPIs than males in both rats and humans (Kumari et al., 2004; Rahman, Kumari, & Wilson, 2003).

Additional neurophysiological investigations relying on auditory stimuli have been used outside clinical settings. One major category includes auditory evoked potentials or ERPs stemming from auditory stimuli.

### EVENT-RELATED POTENTIALS

Components of ERPs in response to auditory stimuli have been used extensively as indices of various stages and aspects of human information processing. ERP components, such as the mismatch negativity component (MMN) and N1, have been used to examine the nature of selective attention (see Naatanen & Alho, 2004, for a review). ERP components have also been used to examine a diverse range of issues, including, but not limited to, distractibility, sleep deprivation, alcoholism, dementia, and schizophrenia. I do not attempt to provide a comprehensive list of the various ways that auditory tasks have been used to examine cognitive processing for this task is well beyond our current scope. Rather, my aim is to highlight some of the many ways that auditory tasks have been used and then to further elaborate on the importance of considering the impact of acoustic characteristics on the mental

workload requirements of these tasks. For example, P300 amplitude and latency are sensitive to both mental workload and to the amplitude of the stimulus; thus, care must be used when interpreting ERP results in neuropsychological evaluations. In general, P300 latency decreases and amplitude increases as auditory stimulus intensity increases (Polich, Ellerson, & Cohen, 1996), which may unfairly disadvantage older, hearing-impaired listeners. Despite this caution, auditory tasks are frequently used to assess brain function.

### **Distractibility**

Auditory tasks have been used to examine the distractibility of different age groups. For example, ERPs in response to an auditory tone while children were engaged in a visual task have been shown to correlate with behavioral measures of distractibility (Gumenyuk, Korzyukov, Alho, Escera, & Naatanen, 2004). Younger children (8–9 years) were more distracted by irrelevant auditory tones than slightly older children (10–11 years and 12–13 years), as demonstrated by increased response time in the visual task and increased amplitude P300 responses to novel auditory tones.

### **Diagnostic Uses of MMN**

The MMN component is an auditory evoked brain response elicited by any discriminable change in repetitive stimuli. It is assumed to be based on an automatic comparison between the infrequently presented stimulus and an auditory sensory memory trace of the frequent sounds (Alain, Achim, & Woods, 1999; Brattico, Winkler, Naatanen, Paavilainen, & Tervaniemi, 2002; Giard et al., 1995; Koelsch et al., 2001). The MMN typically peaks approximately 100–180 ms after presentation of a stimulus that deviates in any discriminable way from a standard held in auditory sensory memory (Cowan, Winkler, Teder, & Naatanen, 1993). MMN typically increases in amplitude and decreases in latency in relation to the stimulus deviation magnitude (Tiitinen, May, Reinikainen, & Naatanen, 1994). Specifically, as the probability of the deviant stimulus increases or if the repetitive stimulus has greater temporal variation, then MMN is attenuated. Other ERP components that detect novel stimuli (i.e., the N1) increase in amplitude only when a new acoustic element is detected, while MMN occurs with both the addition and the removal of acoustic elements (Cowan et al., 1993).

### *Auditory Assessments for Nonverbal Individuals*

It is believed that the MMN component does not require focused attention on auditory stimuli and does not require an overt verbal or manual response (Naatanen, 1992). However, there is some controversy on this point for it has been shown that under certain conditions MMN amplitude can be modulated by focused attention (Woldorff, Hillyard, Gallen, Hampson, & Bloom, 1998). Nevertheless, there is consensus that MMN generation does not require full attention, and that it can be obtained in conditions when the subject cannot or is unable to pay attention. The MMN is therefore useful in assessing auditory functioning in infants and other nonverbal (i.e., comatose) populations. It has also been used to diagnose or assess impairments related to a number of other factors, discussed subsequently.

*Dorsolateral Prefrontal Lesions*

For example, the MMN is reduced in individuals with lesions of the dorsolateral prefrontal cortex (DLPFC; see Naatanen & Alho, 2004; Swick, 2005). Alho and colleagues compared MMN responses to standard 1,000 Hz tones and occasional deviants of 1,300 Hz in individuals with DLPFC lesions and their age-matched controls. Individuals with lesions exhibited reduced MMN responses, particularly when the deviant tones were presented to the ear ipsilateral to the lesion (Alho, Woods, Algazi, Knight, & Naatanen, 1994).

*Sleep Deprivation*

The MMN is sensitive to sleep deprivation. For example, MMN amplitude is present even after prolonged sustained wakefulness. However, Raz and colleagues found that MMN amplitude decreased gradually as participants experienced sustained wakefulness for 24 and 36 hours (Raz, Deouell, & Bentin, 2001).

Auditory tasks have also been used in numerous investigations of age-related changes in cognitive abilities. Because of the well-known relationship between hearing loss and advanced age (Corso, 1963a; Fozard & Gordon-Salant, 2001), considering the mental workload requirements of auditory processing is particularly important in these investigations.

**AUDITORY TASKS IN COGNITIVE AGING RESEARCH**

Cognitive aging research is a domain in which it is particularly essential that careful consideration is given to the characteristics of the acoustic stimuli to be used and the auditory acuity of the participants involved. It is well documented that aging is accompanied by decreased auditory acuity (Fozard & Gordon-Salant, 2001; Humes & Christopherson, 1991; Kline & Scialfa, 1996, 1997; Rabbitt, 1991; Schieber & Baldwin, 1996). As previously indicated, empirical evidence indicated that the acoustic PL of stimuli has an impact on the mental workload requirements of the processing task (Baldwin & Struckman-Johnson, 2002). Therefore, neglecting the impact on performance of a participant's sensory acuity and the PLs of the auditory stimuli involved can seriously undermine interpretation of any results obtained. Overlooking the potential influence of distracting acoustic environments is also problematic as the performance of older listeners is disrupted considerably more than that of younger adults by adverse listening conditions. Unfortunately, studies using auditory tasks often continue to disregard these basic sensory-acoustic parameters.

Examples of investigations in which researchers neglected to assess or at least report the sensory acuity levels of participants and the PLs used for auditory stimuli are abundant. For example, in a recent study, Federmeier and colleagues (2003) used ERPs to chart the time course of acoustic, lexical access, and word context among young and older participants in a sentence-processing task. Their results indicated that older adults on average took 25 ms longer to process the stimulus in the early sensory stages. They then appeared to "make up" for this lost time in the lexical access stage (400 ms postonset), only ultimately to spend an extra 200 ms to process the message-level contextual factors of a sentence. Their findings provided

important cues to differences in the time course of spoken sentence processing between age groups. However, their failure to report either the sensory acuity of their participants or the PLs of their sentences makes it difficult to tease out the full impact of peripheral versus central processing factors. The early processing delay (occurring within the first 200 ms) could be related to age-related changes in the auditory association cortex, as they suggested. Alternatively, this early delay could be due to age-related changes in the outer, middle, or inner ear that result in decreased sensitivity thresholds, thereby resulting in an attenuated signal reaching the auditory association cortex. Therefore, while providing insight into the contribution of sensory and semantic contextual influences on the time course of spoken word processing, their results cannot be as fully appreciated as they might be if age-related differences in pure-tone sensitivity had been taken into account. These age-related sensory-cognitive interactions are discussed in further detail in Chapter 10.

## **SUMMARY**

Auditory tasks are frequently used in cognitive research and, as pointed out in this chapter, many noncognitive factors have an impact on performance of these tasks. In the present chapter, it was only possible to discuss a few of the many auditory tasks that have been used in general cognitive research, research aimed at assessing mental workload, and clinical diagnostic testing. It is hoped that some of the issues raised here help illustrate the importance of understanding the many factors that affect auditory cognition. In particular, prominent issues such as how loudly the stimuli are presented and the hearing abilities of the listeners can have profound influence on performance on these auditory tasks.

## **CONCLUDING REMARKS**

Most of the auditory tasks discussed in the current chapter have involved spoken verbal material. An exception to this was the auditory ERP research involving auditory probes, which are generally tones. In the next chapter, additional attention is devoted to characteristics that influence the mental effort involved in processing nonverbal sounds.

