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What is This?

CHAPTER 2

Auditory Displays for In-Vehicle Technologies

Michael A. Nees & Bruce N. Walker

Modern vehicle cockpits have begun to incorporate a number of information-rich technologies, including systems to enhance and improve driving and navigation performance and also driving-irrelevant information systems. The visually intensive nature of the driving task requires these systems to adopt primarily nonvisual means of information display, and the auditory modality represents an obvious alternative to vision for interacting with in-vehicle technologies (IVTs). Although the literature on auditory displays has grown tremendously in recent decades, to date, few guidelines or recommendations exist to aid in the design of effective auditory displays for IVTs. This chapter provides an overview of the current state of research and practice with auditory displays for IVTs. The role of basic auditory capabilities and limitations as they relate to in-vehicle auditory display design are discussed. Extant systems and prototypes are reviewed, and when possible, design recommendations are made. Finally, research needs and an iterative design process to meet those needs are discussed.

Electronic technologies for passenger vehicles have advanced at a rapid pace in recent years, and many advanced in-vehicle technologies (IVTs) are expected to become ubiquitous in passenger vehicles in the near future. Examples of IVTs include technologies related to the driving task, such as navigation aids and various accident prevention systems, as well as technologies unrelated to driving, such as in-vehicle information systems (IVIS) and entertainment systems, sometimes collectively called *infotainment* systems (see, e.g., Baron, Swiecki, & Chen, 2006; Newcomb, 2010).

Legitimate safety concerns have been raised by both researchers (Donmez, Boyle, & Lee, 2007; Horberry, Anderson, Regan, Triggs, & Brown, 2006) and the general public (e.g., Weiss, 2010) regarding the potential for IVTs to result in driver distraction, a phenomenon that has consistently been identified as one of the primary contributors to automobile accidents (Klauss, Dingus, Neale, Sudweeks, & Ramsey, 2006; Staubauch, 2009). These concerns notwithstanding, IVTs are becoming standard in many new vehicles, and the deployment of IVTs is expected to increase for the foreseeable future (Baron et al., 2006).

Keywords: auditory displays, sonification, in-vehicle technologies, alarms, warnings, auditory icons, spearcons, auditory interfaces

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IVTs present difficult human factors challenges for system designers, but with these challenges come opportunities. Already a wealth of research has begun to evaluate the effects of IVTs on driving performance and safety, and a considerable body of literature has started to inform the best-practice design of interfaces for IVTs, especially with respect to the appropriate display of information to the human vehicle operator. Given that driving is an inherently visual-motor task and that the risk of accidents increases as the eyes linger away from the road (Klauss et al., 2006), the auditory modality has been a promising candidate for safe and successful in-vehicle information display.

Auditory displays can be defined broadly as instances whereby sound conveys information to a user interacting with a system. Audio output and feedback have become a ubiquitous element in human-machine systems as a result in part of engineering improvements in sound delivery capability, most often via digital sound-producing devices (Edworthy, 1998; Flowers, Buhman, & Turnage, 2005; Hereford & Winn, 1994; Kramer et al., 1999). Until relatively recently, technological constraints limited the number and types of sounds that could be built into systems, because physical sound-producing components (e.g., bells, chimes, whistles) were needed for each distinct sound (Edworthy & Hellier, 2006b). Technological advances in electrical systems, and especially in digital computing technologies, however, have made the implementation of a nearly limitless library of high-fidelity sounds possible and indeed pervasive in a vast array of everyday devices, including IVTs.

This review examines the general human factors and design concerns with auditory displays for IVTs. Most current guidelines (e.g., Driver Focus-Telematics Working Group, 2002) offer little in the way of recommendations for designing effective auditory displays for vehicles. We provide an overview of auditory capabilities and limitations that are relevant to the display of information with sound in the vehicle context. Many varieties of auditory displays for in-vehicle applications have been prototyped and developed, and we review extant uses of sound for in-vehicle information display. Of note, we constrain our discussion as much as possible to the role of auditory displays within IVTs; a complete coverage of the complexities of IVTs with respect to controls, visual displays, and system engineering and design is beyond the scope of coverage adopted here. When possible, we examine the empirical literature that offers the clearest guidance for the design and implementation of auditory displays in vehicles. We conclude with a discussion of research difficulties and areas of need for future research, and we discuss an iterative approach to research on auditory display design.

MOTIVATIONS FOR THE USE OF SOUND IN IVTS

The relative advantages and disadvantages of displaying information to the auditory modality have been reviewed extensively elsewhere (Buxton et al., 1985; Hereford & Winn, 1994; Kramer, 1994; Kramer et al., 1999; Sanderson, 2006; Stokes, Wickens, & Kite, 1990; Watson & Kidd, 1994). The auditory system is especially tuned to changes or patterns in sound over time (Bregman, 1990; Flowers, Buhman, & Turnage, 1997; Flowers & Hauer, 1995; Kramer et al., 1999), and in many instances, hearing is better suited than vision for rapid response times (Spence & Driver, 1997). During driving, the line-of-sight requirement of visual displays may make the auditory modality a better option for information display. Similarly, visually information-rich environments, such as those encountered in vehicle cockpits, may overwhelm the eyes when IVTs compete with the driving task for the attention and resources of the visual modality.

Wickens and Seppelt (2002) reviewed a number of studies that compared auditory with visual presentation of information in vehicles. They concluded that auditory information presentation has a pronounced advantage compared with visual information presentation, especially to the extent that the auditory display provides information relevant to the driving task. Another study (Liu, 2001) confirmed that both auditory and multimodal in-vehicle displays resulted in better performance than visual displays on tasks with a navigation system. Given the extremely limited amount of time within permissible safety ranges during which a driver can look at a visual display to interact with IVTs (see Burns & Lansdown, 2000; Kun, Paek, Medenica, Memarovic, & Palinko, 2009), audio has been and will continue to be an integral mode of information display in IVTs.

Current and emerging IVTs have or will have the ability to provide an abundance of information about driving-relevant information, such as collision avoidance and safety warnings, traffic and weather conditions, points of interest, and navigation information. These systems, however, will also be equipped to display a variety of driving-irrelevant information, including Internet, telephone, or e-mail access and in-vehicle entertainment, news, and sports. IVTs represent a domain in which auditory interfaces are all but certain to play a major role in the development of safer, more usable systems.

The inclusion of sound in a system must always be weighed against potential drawbacks, unintended consequences, and the relative merits of sound versus other modes of information display. Annoyance is a perennial concern with the use of sound in systems (Edworthy, 1998; Kramer, 1994). Too many sounds can saturate an environment (Edworthy & Hellier, 2000), and unreliable alarms harm performance in systems (Cummings, Kilgore, Wang, Tijerina, & Kochhar, 2007). False alarms are potentially a serious problem with in-vehicle collision warning systems because of the low base rate of accidents (Parasuraman, Hancock, & Olofinboba, 1997). Faced with these potential dilemmas with auditory displays, researchers and designers must be careful to choose the right information to represent with sound, choose the right sound to represent the information, and make decisions about how the sound is implemented in a system that are informed by research and evaluation.

BASIC AUDITORY CAPABILITIES AND LIMITATIONS IN THE IVTS CONTEXT

With any system, the design must begin with a consideration of the basic capabilities and limitations of the human operator of the system. We mention some of the most relevant background with respect to auditory display design, but issues related to sensing and perceiving sounds, auditory and multimodal attention, and auditory memory have been covered extensively elsewhere (see, e.g., Bregman, 1990; Gelfand, 2009; McAdams & Bigand, 1993; Spence & Ho, 2008a). Detectability, discriminability, and identifiability are fundamental sensory-perceptual tasks that impose successively greater

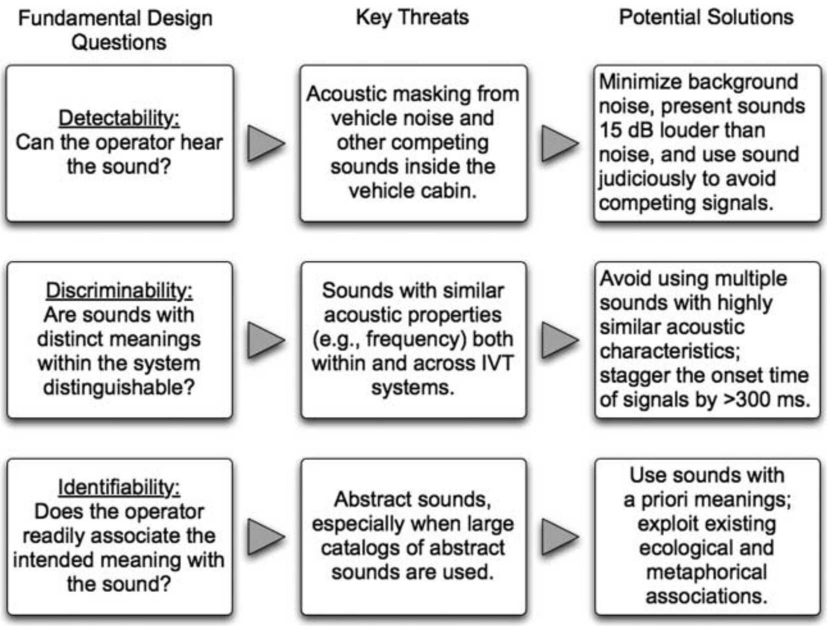

Figure 2.1. *Fundamental auditory display design questions, threats, and solutions. IVT = in-vehicle technology.*

demand on the listener. Detection is noticing that a sound occurred, discrimination is noticing that two sounds are different, and identifiability is recognizing the identity or meaning associated with a specific sound.

Perhaps the three most fundamental axioms of auditory interface design correspond to detection, discriminability, and identifiability, respectively: (a) Use sounds that people can hear; (b) when sounds are used to represent distinct system states, use sounds that people can perceive as being different; and (c) use sounds for which people can identify the intended meaning. Figure 2.1 shows some of the key threats and potential solutions to these primary design concerns with auditory displays. Further considerations include attention and memory for sounds. The potential for sound to cause annoyance or be laden with affective content are also important to consider when designing auditory displays.

Detectability

The basic detection thresholds of the human auditory system vary as a function of the frequency of the sound and are fairly well understood for experimental stimuli in highly controlled listening conditions. Lower thresholds—meaning greater sensitivity to sounds—can be expected for frequencies between 100 Hz and 10000 Hz, with maximal sensitivity to sounds between 2000 Hz and 5000 Hz (Gelfand, 2009). These models, however, do not necessarily directly translate to guidelines for presentation levels for auditory interfaces when the constraints of context are considered (Watson & Kidd, 1994). Masking of the signal by other sounds (e.g., human speech, radio music, or road noise) or masking of other important sounds by the signal are important concerns for auditory displays in vehicles.

The prediction of road noise alone is a function of numerous variables related to the vehicle, road, and driving conditions (Yamauchi, Kamada, Shibata, & Sugahara, 2005), and the co-occurrence of sounds in a vehicle cockpit may be difficult to anticipate. An auditory interface should be tested for detectability of all sounds in the range of operating conditions in which the system is expected to function.

When a single, static measurement of background noise is taken to represent an acoustically complex and dynamic environment, problems with the detectability of sounds may emerge. For example, a designer might be tempted to simply take one measurement of the baseline background noise in the vehicle and deliver a critical auditory warning at a level above this baseline measurement. Consider, however, that during the critical event that triggers the warning, the vehicle cockpit may be saturated with other alerts or warnings and other environmental sounds that were not present during the baseline measurement. If multiple auditory alarms are triggered by events that are individually rare but likely to occur together during an emergency or critical driving moment, then problems with detection and identifiability of the individual signals may arise at the least opportune moment (e.g., Edworthy & Hellier, 2000, 2006a; Lacherez, Seah, & Sanderson, 2007; McGookin & Brewster, 2004).

Some current and most future systems may be able to compensate for these types of problems by incorporating sound level monitoring into the auditory interface and automatically adjusting the level of warnings to allow for maximum detectability (see Peryer, Noyes, Pleydell-Pearce, & Lieven, 2010). Except for perhaps the most critical alarms, designers should generally avoid the temptation to simply make a sound louder to overcome masking, as another challenge for ergonomic auditory interface design is to avoid making the sound too loud. Thresholds of discomfort for complex acoustic stimuli vary widely from person to person (Warner & Bentler, 2002) and should be established in a representative driving context and avoided.

In addition to ambient and incidental noise, the potential for intentional sounds to be masked by one another becomes a threat to detection as auditory interfaces in the vehicle propagate. Masking has unintentionally occurred when the auditory displays were not explicitly designed to avoid peripheral acoustic interference (see, e.g., Donmez, Cummings, & Graham, 2009). Research has offered fairly unanimous evidence that the detectability, discriminability, and identifiability of sounds all become more difficult as concurrent sounds become more numerous, particularly when the sounds are similar (Bonebright, Nees, Connerley, & McCain, 2001; Ericson, Brungart, & Simpson, 2003; Lacherez et al., 2007; McGookin & Brewster, 2004; Walker & Lindsay, 2006a).

Designers must also consider the possibility that sounds from the auditory interface will mask crucial communications, such as concurrent speech. Early research (Stevens, Miller, & Truscott, 1946) suggested that tones in the frequency range of 100 Hz to 500 Hz are most likely to mask concurrent speech signals. Whereas we have emphasized the very real potential for interference and masking to occur when sound stimuli occur concurrently, some research has shown little to no interference for competing signals. For example, Leshowitz and Cudahy (1973) found no interference for a tonal discrimination task accomplished in the presence of another distractor tone except for conditions when the signal tone was exceedingly brief (10 ms) and occurred in the same ear as the distracting tone. Results such as this suggest that it will be possible to design effective auditory displays that do not mask one another or other relevant acoustic information.

Although concurrent sounds can and should be designed to avoid peripheral acoustic masking, the best design may sometimes incorporate other display modalities or multimodal signals if acoustic noise is a pervasive and unavoidable aspect of the environment. Edworthy (Edworthy & Hellier, 2005, 2006a), for example, has often argued that auditory alarms are overused. We also note that the avoidance of peripheral masking does not necessarily ensure that two auditory signals will not interfere with each other at more central or cognitive levels of information processing (see Durlach et al., 2003). The limitations on the number and types of auditory and multimodal signals that can be perceived and processed without masking in driving scenarios is an important area of research need.

Discriminability

Discriminability refers to the extent to which a person can tell that two signals are different. The potential for auditory displays to sound too similar has been identified as a concern for system operators (Ahlstrom, 2003). The literature abounds with examples of studies of discrimination for sound dimensions, such as pitch (Stevens, Volkmann, & Newman, 1937; Turnbull, 1944), loudness (Stevens, 1936), tempo (Boltz, 1998), and duration (Jeon & Fricke, 1997). A number of factors, including background noise, the similarity of the two signals (Aiken & Lau, 1966), and the time elapsed between signals before the comparison is made (Aiken, Shennum, & Thomas, 1974), may affect the discriminability of two signals.

Auditory discrimination behaves somewhat like an ability in that it can be improved with practice (Auerbach, 1971), but the best approach for design is to simply avoid thresholds of discrimination on relevant acoustic variables altogether. Although laboratory studies have determined discrimination thresholds in extremely controlled conditions, the boundaries of discrimination are difficult to predict with a generic heuristic in ecological settings. The potential complexity of the stimuli used in auditory displays and the variant environmental noise conditions in which IVTs are deployed make at least minimal testing of sounds a necessity in most instances when sounds with different intended meanings in the interface share similar acoustic characteristics.

Identifiability

Identifiability is the extent to which an operator can associate the appropriate label, action, or distinct intended meaning with a given auditory signal. In general, identifiability will likely be limited to a small set when abstract sounds are used (Watson & Kidd, 1994). An identification task that required assigning a verbal label to each tone from a catalog of six tones that were differentiated by frequency showed just better than 50% performance across 10-s, 30-s, and 60-s retention intervals—a finding suggesting that identification was not especially good and also was not sensitive to the length of the intervening retention period (Aiken et al., 1974).

More meaningful sounds may help aid in identifiability. Research has shown that sounds that bear an ecological resemblance or other established relationship to their meaning in the system context are easier to identify than abstract sounds (e.g., tones) with no inherent relationship to their referent (Bonebright & Nees, 2007; McKeown & Isherwood, 2007; Palladino & Walker, 2007; Perry, Stevens, Wiggins, & Howell, 2007; Smith, Stephan, & Parker, 2004). Identifiability appears to be a problem in many current IVTs that use beeps, tones, or chimes. A recent study (Jenness, Lerner, Mazor, Osberg, & Tefft, 2008) surveyed drivers' opinions about their adaptive cruise control systems. Only 49% of respondents agreed that the system's sounds were easy to understand, compared with 73% agreement for the same question regarding the system's visual displays.

Preattentive Auditory Processing and Auditory Attention

Bregman's (1990) work on auditory scene analysis has been particularly influential in motivating design choices in auditory displays. The theory essentially describes how a sound scene is parsed according to a multitude of acoustic cues preattentively—that is, before the listener makes any conscious or top-down effort to attend to sounds. Scene analysis is an adaptive process whereby the auditory system segregates sounds into probable physical sources. Some compelling examples of the streaming of sounds based on different acoustic properties are widely available (see, for example, http://webpages.mcgill.ca/staff/Group2/abregm1/web/downloadsdl.htm).

When a series of high-pitched and low-pitched tones are played relatively slowly, they are perceived as a stream of alternating tones, presumably emanating from the same physical source. When the same alternating tones are played at a faster rate, however, the percept decomposes into two distinct perceptual streams—one a series of higher pitched tones and the other a series of lower pitched tones—seemingly emanating from different physical sources. Perceptual segregation, then, is the separation of concurrent or temporally proximal sounds into distinct streams associated with distinct sources, which are adaptively perceived as distinct auditory objects.

Some strategies to promote perceptual segregation (Bregman, 1990), and thereby reduce interference from concurrent sounds, include spatially separating sounds (e.g., Bonebright et al., 2001; Brown, Brewster, Ramloll, Burton, & Riedel, 2003), using distinct timbres for each sound (Bonebright et al., 2001; Cusack & Roberts, 2000; McGookin & Brewster, 2004), and lagging the onset of concurrent sounds (e.g., by 300 ms; see McGookin & Brewster, 2004). Separating sounds with pitch and register differences to promote concurrent perception is possible, but this option is less attractive (Brewster, 1994), especially when the auditory display uses pitch change to represent changes in other relevant (e.g., quantitative) information dimensions. Knowledge of this preattentive process can be used to design concurrent auditory displays that are perceptually distinct.

In the most broad sense, it is generally understood that sound is particularly effective (compared, for example, with vision) at attracting conscious attention (Spence & Driver, 1997). After a sound has captured a person's awareness, attention often is discussed further in terms of selective attention, or the ability to attend to a particular aspects of a sound stimulus. The function of selective attention is effectively to enhance the listener's perception of certain acoustic attributes, perhaps at the expense of other attributes, and there is evidence to suggest that the effects of selective attention are observed in the auditory system as early as 20 ms after hearing a sound (Woldorff et al., 1993). Attention can be selectively cued to characteristics of sound, such as frequency (Mondor & Bregman, 1994) or the location of a sound (Mondor, Zatorre, & Terrio, 1998; Woods, Alain, Diaz, Rhodes, & Ogawa, 2001). The saliency of particular cues in selective attention tasks may change with task and stimulus demands.

Woods et al. (2001), for example, found that frequency was generally a more powerful cue for selective attention than spatial location, particularly for sounds with a fast rate. An auditory display designer can reasonably expect listeners to be able to selectively pay attention to particular aspects of sound, such as frequency, tempo, or spatial location.

Although "parallel listening"—the simultaneous processing of multiple audio streams—has been touted as a potential benefit of auditory displays (Kramer, 1994; Kramer et al., 1999), there will most certainly be an upper limit to the number of concurrent auditory streams that can be successfully attended (Flowers, 2005). This theoretical limit has yet to be determined and will likely be a function of both acoustic properties of the sounds and the demands of the task at hand. Unless careful evaluations are conducted to confirm the viability of multiple auditory streams, system designers should generally limit the number of concurrent sounds.

Although the threshold for the number of concurrent sounds will be determined by the required level of accuracy within the system, research has generally shown that accuracy in identifying acoustic signals decreases linearly as the number of concurrent sounds increases (e.g., Ericson et al., 2003; McGookin & Brewster, 2004). McGookin and Brewster (2004), for example, showed that the recognition of abstract sounds called earcons decreased from 70% to 30% accuracy as the number of earcons presented increased from one to four, and more than two or three concurrent sounds will result in unsuitable performance for most systems.

Auditory Cognition and Auditory Memory

With IVTs, information may be presented to the operator prospectively such that the information must be retained for a period before a decision or action is required. The ephemeral nature of auditory interfaces may create demands on memory as system operators try to internally rehearse sounds that have already been presented. Auditory memory and the cognitive aspects of listening to a large extent have been overlooked in the literature. Kramer (1994) suggested that some tasks with sound may involve matching percepts to stored templates in memory, but the nature and origin of stored templates for sound are fairly unknown.

A number of findings from both behavioral studies and neuroscience support the notion that overlearned (e.g., frequently heard) acoustic stimuli, such as well-known songs (Halpern, 1988, 1989; Schellenberg & Trehub, 2003), familiar voices (Nakamura et al., 2001), and environmental sounds (Ballas, 1993), are retained with fairly precise and seemingly permanent representations of the acoustic properties of the stimulus.

Whereas previous theorists (e.g., Neisser, 1967) had pegged the duration of the sensory acoustic store (dubbed *echoic memory*) at just a couple of seconds, recent research has suggested that novel acoustic stimuli may linger in a fairly veridical sensory-acoustic form in memory for a period of at least 10 s (Cowan, 1984) and perhaps up to 30 s (Winkler et al., 2002) or longer following the hearing of a novel sound.

The context of auditory memory tasks matters, however, as performance suffers when the retention interval is filled with other tonal stimuli (Deutsch, 1970) or stimuli that have acoustically similar characteristics (e.g., Starr & Pitt, 1997). In general, research suggests that auditory memory is good for well-learned sounds for indefinite periods, and acoustic characteristics of novel sounds seem to be adequately recalled for at least several seconds following stimulus presentation.

Annoyance

Sounds undoubtedly have the potential to annoy system operators, and annoyance remains a major concern for auditory display design (Edworthy, 1998; Edworthy & Hellier, 2005, 2006a; Kramer, 1994). Annoying sounds run the risk of being simply turned off or ignored by the system operator (Edworthy & Hellier, 2006a). Since aesthetics and performance benefits are largely independent, annoying sounds may even be turned off when they positively affect performance of tasks within a system (Edworthy, 1998). Likewise, a poorly designed sound that does not accomplish functional goals in the interface may be perceived as aesthetically displeasing regardless of its standalone acoustic appeal (Leplatre & McGregor, 2004).

Miller (1947) chronicled a number of acoustic features that increased annoyance, including sounds with higher frequencies, larger versus restricted ranges of pitch intervals, pulsing beats, randomly varying durations of tones, and slow rates of sound repetitions. High-pitched sounds seem to be particularly susceptible to creating annoyance (Bonebright & Nees, 2007). In a recent study (Bonebright & Nees, 2009), a variety of sounds, including brief speech messages and abstract sounds based on pitch and timbre motifs, were all rated as neutral or somewhat annoying to participants. The use of musical sounds has been suggested to ease perceptibility and perhaps combat annoyance (Brown et al., 2003; Childs, 2005), and researchers (Morley, Petrie, O'Neill, & McNally, 1999) have reported high user satisfaction with some nonspeech sounds in interfaces.

Sound as a Carrier of Affect

Sounds can carry emotional content and associations that may affect their effectiveness in interfaces. The perception of urgency in a warning sound (discussed later), for example, may elicit an emotional response, and particularly sudden, loud, or unexpected sounds may elicit undesirable, innate startle responses. A study (Weger, Meier, Robinson, & Inhoff, 2007) showed that the affective content of concurrent verbal stimuli systematically biased tone judgments. Although the verbal stimuli were irrelevant to the tone judgment task, participants were faster and more accurate at classifying the tones as high or low in pitch when the metaphorical direction of the verbal prime was consistent with the tone stimulus (i.e., when higher pitched tones matched positive words and low-pitched tones matched negative words). Findings such as this suggest that the affective components and associations of sounds may be influencing the performance of some tasks in ways that designers do not fully understand.

Findings from one study suggested that emotionally charged warning sounds in IVTs do not improve—and may even have a negative effect on—driving performance as compared with conditions with no sounds or a tone warning (Di Stasi et al., 2010). The affective content of sound and the related associations thereof have not been fully explored, and more research is needed to understand the extent to which the emotional impact of sound can be leveraged for uses in interfaces or, when necessary, designed around or out of auditory displays.

BRIEF DESCRIPTIONS OF TYPES OF AUDITORY DISPLAYS AND DESIGN APPROACHES

Taxonomic descriptions of auditory interfaces could be arranged by either the form of the sounds or the function of the sounds in the system, yet neither approach would delineate hard definitional distinctions. The boundaries between categories in taxonomic descriptions of auditory interfaces are blurry. In the interest of providing an introductory overview, we describe the types of sounds that commonly have been used in auditory displays, including IVTs and prototype systems. Although this overview does not constitute a complete terminology of auditory displays, it does provide a brief background on some of the technical terms that are common in auditory display design. Table 2.1 gives an overview of the types of auditory displays that are either currently used or might potentially be used in IVTs. Our descriptions are intentionally brief, as other taxonomies and descriptions of auditory displays are available elsewhere (Buxton, 1989; de Campo, 2007; Kramer, 1994; Nees & Walker, 2009). For a very thorough glossary of auditory display terminology, see Letowski et al. (2001).

Auditory icons (Gaver, 1989, 1994) are brief sounds that have some a priori association with their referent object, event, or process. The relationship between the sound and its meaning in the interface can range from quite literal (e.g., the sound of crackling flames to represent an engine fire) to more metaphorical (e.g., the sound of crumpling paper to represent a computer file being deleted) (see Keller & Stevens, 2004).

Earcons are abstract sounds that systematically employ repetitive melodies, rhythms, and so on to represent families of referents, such as the elements of a hierarchy (Blattner, Sumikawa, & Greenberg, 1989). In a menu structure, for example, a combination of musical notes, such as C and C-sharp, might represent "File > Save," whereas the notes C and D might represent "File > Save as." The C note in this example would indicate "File" in the hierarchy.

Some auditory interfaces have used *environmental and naturalistic sounds* to convey information. Environmental and naturalistic sounds have complex acoustic properties (e.g., as compared with pure tones; see next paragraph). For brief sounds, this approach is essentially indistinguishable from using auditory icons with direct relationships between the sounds and their referents.

Table 2.1. Common Types of Sounds Used in In-Vehicle Technologies

Sound Class	*Primary Properties*	*Strengths*	*Weaknesses*
Auditory icons	Sounds that are ecologically associated with referents	Easily learned, not prone to masking	Relatively inflexible
Earcons	Abstract sound families with no prior association with referent	Flexible, not prone to masking	Relatively difficult to learn
Environmental sounds	Complex natural sounds	Easily learned, not prone to masking	Relatively inflexible
Musical tones	Complex tones from musical instruments with multiple harmonics	Flexible, less prone to masking	Relatively difficult to learn
Pure tones	Tones of a single frequency with no harmonics	Flexible	Prone to masking, relatively difficult to learn, annoying
Sonifications	Audio representations of quantitative data	Can represent more complex quantitative data	Moderately difficult to learn
Spatialized audio	Audio emanating from a spatial location within the vehicle	May guide attention to the location of a potential hazard	More intensive to implement than nonspatialized sound
Spearcons	Accelerated speech phrases	Flexible, easily learned or no learning required	Phrases must be brief
Speech	Sounds of the human voice, either prerecorded or delivered via text-to-speech algorithms	Flexible, no learning required	Often slow and lengthy, may interfere with conversation
Spindex	Very brief sounds of letters of the alphabet appended to the beginning of long auditory menus	Flexible, no learning required	Useful only for alphabetized lists of information
Trendsons	Brief sonifications that embed information about trends in system states	Conveys both qualitative and quantitative information	May require learning, annoyance is possible

Musical tones, such as those found in the Musical Instrument Digital Interface (MIDI) bank, have been used in many auditory displays, especially in earcons and sonifications of data. Some researchers (Brown et al., 2003) have suggested that musical tones are a better choice for sounds in auditory interfaces than tones of a single frequency, called *pure tones*, and these sounds have been used and remain common as crude auditory displays in many devices. In general, pure tones are less preferable to more complex sounds because of both aesthetics and the susceptibility of a single frequency to masking effects (Rossing, 1982).

Sonification is broadly defined as "the use of nonspeech audio to convey information" (Kramer et al., 1999, Section 1). This definition applies to every nonspeech audio interface element discussed here, but the term *sonification* is often used to refer specifically to auditory displays of quantitative data (rather than auditory icons and earcons, etc.). *Auditory graphs* (Flowers & Hauer, 1992, 1993, 1995) are a class of sonifications that are auditory analogs to the Cartesian coordinate graphs that pervade textbooks and popular publications. Auditory graphs typically map changes in quantitative data to corresponding changes in the pitch of tones or musical notes over time.

Spatialized audio refers to the separation of sound sources in space. The separation often occurs as a function of the real separation of sound sources, such as the use of two speakers at left and right locations in common stereo sound systems. Two-point, left-and-right stereo separation of sounds can more accurately be called *lateralized audio*, as the apparent source of the sound signal can be moved in space across the lateral dimension (e.g., from left to center to right). Presenting sounds such that they seem to come from a specific location in space that has both lateralization and depth around the listener is called 3-D or spatialized audio (see Wightman & Kistler, 1983).

Spearcons (Walker, Nance, & Lindsay, 2006) are brief, accelerated speech sounds. Spearcons are made by taking a brief speech sound (often synthesized via text-to-speech [TTS]) and compressing the sound in time. Spearcons are created with the use of a constant-pitch algorithm that avoids the high-pitched voice effect associated with speeding up speech sounds. A close relative of spearcons, *spindex* (speech index) audio cues accelerate the spoken letters of the alphabet to provide an auditory analog to the alphabetical Rolodex (Jeon & Walker, in press). Spindex cues are usually prepended to a list of alphabetized auditory items to help speed up searches through long lists in auditory menus.

Speech sounds are the sounds of the human voice. Speech can involve prerecorded, natural voicings, but this approach is cumbersome and requires the designer to anticipate and prerecord every possible message to be presented by the interface. More often, synthetic speech is generated in interfaces via TTS translations.

Trendsons (Edworthy, Hellier, Aldrich, & Loxley, 2004) are akin to brief sonifications that report information to the listener about a trend in some variable. Edworthy et al. (2004) evaluated trendsons for use in monitoring vital parameters in a helicopter cockpit. A related approach is Watson's (2006) scalable earcons. Each of these types of sounds maintains some of the brevity of shorter, iconic sounds while also embedding an acoustic representation of the quantitative state of data from an ongoing process.

An important final point to discuss is the relationship between abstract sounds, ecological sounds, and the entities that these sounds reference in an interface. The relationship between a sound and its referent process exists along a continuum that ranges from purely symbolic or abstract relationships between the sound and its referent to purely literal and direct relationships between the sound and the event or process it represents (Kramer, 1994). In the most direct case, a sound represents its ecological antecedent or cause directly, such as when the sound of crackling flames represents, quite literally, a fire. Other ecological relationships include indirect-ecological (whereby related but not literal ecological sound associations are used, such as the sound of tree branches breaking to represent a tornado) and indirect-metaphorical (whereby the sound and its referent are similar by analogy, such as a mosquito buzzing to represent a helicopter) relationships (Keller & Stevens, 2004).

Abstract sounds, such as tones and earcons, have symbolic relationships with their referent process, and symbolic relationships generally must be learned in the context of the interface. Abstract relationships may allow for more flexibility in the representation of different processes; any interface element can be represented via a symbolic association with no inherent relationship between the sound and its referent. The problem, however, is that abstract sounds are more difficult to learn and remember than sounds with some relationship to their referent (Bonebright & Nees, 2007; McKeown & Isherwood, 2007; Palladino & Walker, 2007; Perry et al., 2007; Smith et al., 2004), and some research has indicated that direct relationships are most easily learned (Keller & Stevens, 2004; Stephan, Smith, Martin, Parker, & McAnally, 2006).

The caveat to this rule, however, is speech. With the exception of onomatopoeia, language has no ecological association with its referents. Yet the symbolic associations of language are so overlearned that speech and speechlike sounds (e.g., spearcons and spindex) tend to be easily learned and effectively used in interfaces (Bonebright & Nees, 2009; Jeon & Walker, in press; Palladino & Walker, 2007; Smith et al., 2004).

AUDITORY DISPLAYS FOR IVTS: EXTANT SYSTEMS AND PROTOTYPES AND POTENTIAL EXTENSIONS

Audio has already seen widespread implementations in many in-vehicle systems, although extant applications of sound in IVTs have yet to leverage the richness of sound for information display. The sounds of most systems default to minimally informative tones, chimes, and beeps. A number of other design possibilities have been successfully prototyped for IVTs or tested in research scenarios that may readily generalize to in-vehicle auditory information display. We group our discussion of auditory displays for IVTs into four categories: (a) collision avoidance and hazard warning systems, (b) auditory displays that alert the operator to his or her state or the conditions of the vehicle itself (e.g., low fuel), (c) auditory displays for interacting with IVIS, and (d) auditory displays that aid navigation.

Collision Avoidance and Driving Hazard Warning Systems

Warnings typically indicate a negative system state that requires immediate attention or action. For IVTs, a warning will likely indicate an unsafe driving scenario, such as a potential accident hazard, and auditory warnings may capture and orient attention more effectively than visual warnings (for a review, see Spence & Driver, 1997). Auditory warnings research has amassed a considerable literature that includes numerous sets of design guidelines (e.g., Ahlstrom, 2003; Campbell, Richard, Brown, & McCallum, 2007; Edworthy & Hellier, 2006b). Edworthy and Hellier (2006a) identified four characteristics of the ideal alarm as (a) easily localizable in space, (b) not susceptible to masking by other sounds, (c) not a source of interference with other communication (e.g., speech), and (d) easily learned and remembered.

In addition to meeting minimal acoustic parameters for localizability and detectability, auditory warnings need to be informative enough to provide the system operator with some indicator not only of the adverse event but ideally also of its nature and perhaps even of corrective actions to be taken. Although auditory warnings that match the operator's current informational needs are preferable to less informative, generic warnings (Seagull, Xiao, Mackenzie, & Wickens, 2000), a warning needs to be brief enough to relay a message as efficiently as possible to allow time for the operator to act. As such, both nonspeech sounds, such as tones, earcons, and auditory icons, as well as brief speech messages have been used as warnings in vehicles.

Researchers (Edworthy & Hellier, 2006b; Patterson, 1990) have arrived at the consensus that auditory warnings should be presented at least 15 dB higher than background noise, and Edworthy and Hellier (2006b) advise that warning signals should not exceed the background noise intensity by more than 25 dB. This offers some guidance for auditory warning design, as sound level meters capable of establishing a rough baseline level of noise in a given environment are relatively inexpensive and widely available. The interested reader is referred to Mulligan, McBride, and Goodman (1985) for detailed flow charts to aid in the design of nonspeech signals that are detectable in noise and Giguere, Laroche, Osman, and Zheng (2008) for a detailed methodology for optimizing the presentation of warnings in noisy environments.

In some systems, when an adverse event is particularly important or takes precedence to other concurrent system information, it may be important to design urgency into the auditory signal. Haas and Edworthy (1996) showed that the perceived urgency of an auditory signal increases as the loudness, pitch, and speed (i.e., rate) of the sound increased, with increases in loudness and pitch also resulting in faster responses. Other researchers (Guillaume, Pellieux, Chastres, & Drake, 2003), however, have shown that although the perceived urgency of an auditory warning is generally predictable from acoustic properties, the notable exceptions to this rule were instead explained by learned associations and cognitive representations of sound meaning.

In Guillaume et al.'s (2003) study, for example, a stimulus that sounded like a bicycle bell should have resulted in a high urgency rating on the basis of predictions from acoustic models, but the sound was rated as having low perceived urgency. The researchers speculated that the cognitive representation of meaning for a bicycle bell overrode the urgency conveyed by the acoustic signal. Other research (Burt, Bartolome, Burdette, & Comstock, 1995) has indicated that the perceived urgency of a signal may change as the demands on the system operator change. A general rule regarding auditory warnings seems to be that increasing certain acoustic properties, such as frequency, intensity, and the temporal rate of a signal, will usually increase perceived urgency, and people subjectively feel that urgent auditory warnings are appropriate for driving situations that are associated with high urgency (Marshall, Lee, & Austria, 2007).

Interestingly, however, the perceived urgency of a signal does not necessarily correlate with a faster objective response to the signal. A study (Sanderson, Wee, & Lacherez, 2006) tested auditory warnings that were designed according to a published international standard and found that participants perceived the standard's "high-priority" alarms to indicate more urgency, yet they tended to respond faster to "medium-priority" sounds from the standard.

Collision Avoidance System (CAS)

A CAS is an IVT that uses visual, auditory, or tactile warnings to inform the driver of potential impending accidents during which the vehicle is at threat of leaving the roadway or contacting other vehicles or objects. Varieties of CAS include adaptive cruise control, blind spot warnings, reverse warnings, lane departure warning systems, and rear-end collision avoidance systems. Researchers and designers have frequently used tones or noise bursts in studies of CAS, but other types of sounds may be more effective.

Adaptive cruise control systems, for example, have begun to appear as a safety feature in many vehicles. Typically, the systems detect distances from a lead vehicle and automatically adjust the vehicle's speed to maintain safe distances from lead vehicles when cruise control is engaged. Sound warnings in such systems indicate potentially dangerous states (e.g., collision threats) in which the driver needs to intervene with the system, and sounds may also indicate the engagement or disengagement of the system. Currently, the types of sounds used in adaptive cruise control systems seem to be simple, abstract beeps, chimes, and tones.

Lin and colleagues (2009) recently tested the effectiveness of various types of simple auditory alerts for lane departures. Tone bursts and continuous tones of 500 Hz, 1750 Hz, and 3000 Hz were examined. Response times were significantly faster at 1750 Hz and 3000 Hz as compared with 500 Hz, and there were no differences for bursts versus continuous tones. Participants overwhelmingly felt that the bursts made better warnings, however, and most participants felt the 1750 Hz tone was the best choice for frequency.

Lee, McGehee, Brown, and Reyes (2002) reported that a multimodal warning to indicate that a lead car was breaking significantly decreased collisions by 81% when the warning occurred close in time to the onset of braking. Later warnings were less effective but still showed improvement compared with no warnings, and the warnings improved performance for both distracted and undistracted drivers. The visual component of the warning was an icon above the instrument panel, and the auditory component consisted of pulsing bursts centered around 2500 Hz and presented 2 dB to 5 dB above ambient noise conditions, depending on the speed of the vehicle.

Findings from another study (Suzuki & Jansson, 2003) suggested that both monaural and spatially predictive stereo auditory warnings (beeps) were less effective (i.e., resulted in slower reaction times) for correcting lane departures than haptic feedback delivered via the steering wheel when participants were naive to the meaning of the warnings. When participants were instructed on the meaning of the warnings, performance was equivalent for both auditory and haptic warnings. Interestingly, the researchers found that stereo warnings to predict the side of the lane departure did not facilitate corrective steering away from the departure. Instead, the participants looked ahead at the road before taking corrective actions with steering, despite the fact that the location of the tone indicated the direction of the departure.

The finding by Suzuki and Jannson (2003) that training on the meaning of an auditory warning improves performance suggests that abstract tones and beeps may not make the most intuitive signals for collision warnings in IVTs. To this effect, a number of studies have shown that auditory icons likely offer a better option for warning sounds in vehicles. A study (Belz, Robinson, & Casali, 1999), showed that auditory icons (the sound of tires skidding for an imminent front or rear collision and the sound of a horn honking for an imminent side collision) produced significantly faster breaking response times than did tones, a visual warning condition, and a control condition without warnings. Furthermore, the auditory icon display alone resulted in performance that was as fast as several multimodal conditions. In addition, auditory icons showed a considerable advantage compared with tones for identifiability of the meaning of the auditory signal, and participants generally preferred a multimodal display.

A similar experiment (Graham, 1999) found that the same auditory icons (a car horn and skidding tires) resulted in faster braking response times than did a tone or a speech warning ("ahead"), but the auditory icons also elicited more false-positive braking in inappropriate situations. The car horn in the study was perceived by users to be an appropriate indicator for a potential collision, and the tone was perceived to be the least appropriate and least liked warning. Auditory icons represent a simple change away from the typical tone warnings of traditional interfaces, yet this small change might result in considerable safety advantages. Furthermore, in a recent study (McKeown, Isherwood, & Conway, 2010), a stronger ecological relationship between an auditory icon warning and an impending potential rear-end collision event improved reaction times, which led the authors to suggest that auditory icons act as "occasion setters" that prime reactions.

Spatial Audio for Collision Warnings

For many potential sources of collisions, knowledge of the location of the threat may offer relevant information and potentially suggest corrective action to the driver. Sounds emanating from a spatial location can capture visual attention and actually facilitate visual perception (McDonald, Teder-Salejarvi, & Hillyard, 2000); the implications of this cross-modal facilitation may be very important for collision avoidance in vehicles. In one study, nonspeech sounds that spatially cued drivers to the location of a simulated event requiring intervention (braking or accelerating) produced large improvements in response times (Ho & Spence, 2005). Ho and Spence (2009) further showed that people oriented faster (i.e., had a faster head movement response time) to auditory warnings presented close behind them (40 cm behind their heads) as compared with a waistline vibrotactile warning, a peripheral visual warning, or a condition in which the auditory warnings were farther away (80 cm) and in front of them—a location that roughly corresponds to the location of in-dash radio loudspeakers in many vehicles.

In another study, however, no difference was found in driver response times between a condition that used a generic master alarm (abstract tone patterns) to warn of a potential danger as compared with a series of multiple distinct abstract sounds that indicated more specific information about the location and type of danger (Cummings et al., 2007), so clearly, this is an area where further research would elucidate more conclusive evidence and design heuristics. Spatialized audio presentation, however, offers another feasible approach to alerting the driver to possible collision hazards (or the cockpit pilot to possible targets, etc.). For sounds that are maximally localizable, Edworthy and Hellier (2000) recommended the use of sounds with multiple harmonics and low fundamental frequencies (also see Wightman & Kistler, 1983).

AUDITORY ALERTS FOR VEHICLE AND DRIVER CONDITIONS

In much of the literature, auditory alerts are synonymous with warnings. We define *alerts* here as brief messages that assume a lower priority than warnings. These signals may not necessarily indicate a negative system state and also may not require immediate action. Auditory icons, earcons, musical sounds, pure tones, speech messages, and spearcons are all candidate types of sounds for alerts and reminders. Alerts and reminders may convey information to the system operator about ongoing processes, prospective actions to be taken at a later point in time, or optional courses of action.

Speed Alerts

Systems that use intelligent speed adaptation operate along a continuum that ranges from passive alerts to active interventions that are intended to ameliorate violations of posted speed limits. Passive alerts include auditory or visual alerts that are activated when a driver exceeds the speed limit, and the most intrusive systems might actively disable acceleration for speeding violations (Carsten & Tate, 2001). A system that used a beeping tone alert to indicate to drivers that speed limits were being exceeded was successful in reducing driver speeds, although a system that exerted accelerator counterforce resulted in slightly better speed reductions. The beeps turned into a continuous tone for egregious speeding violations. Interestingly, participants found the beeps annoying, perhaps in part because of the design of the sounds, yet they generally preferred and were more accepting of the warnings as compared with the accelerator counterforce system (Adell, Varhelyi, & Hjalmdahl, 2008).

Users may be unwilling to accept more intrusive systems in which perceived control of the vehicle is forfeited (Varhelyi, 2002), and thus auditory alerts may continue to be an integral component in such systems. More informative alerts, such as auditory icons, will likely result in less annoyance with the system sounds and perhaps even facilitate further increases in speed limit compliance.

Vehicle Malfunction Alerts

Auditory alerts have also been investigated for indicating malfunctions or other critical information about the operational status within a cockpit. Although some of this work has focused on aircraft cockpit warnings, the results of such studies remain relevant for IVT design. Haas (1998) found that the response time to a visual alert for helicopter malfunction was not as fast as the response to a visual alert plus spatial speech or a visual alert plus a spatialized auditory icon. Auditory icons were more easily learned and were associated with better reaction times than abstract auditory warnings in another study of cockpit warnings for events such as low fuel and icing (Perry et al., 2007). Smith, Stephan, and Parker (2004) found that speech warnings for cockpit events and malfunctions produced the fastest response times, compared with auditory icons and abstract sounds, across several manipulations of increasing workload, and they also found that speech and auditory icons were equally learnable, whereas learning for abstract sounds was worse.

McKeown and Isherwood (2007) compared the identifiability of abstract sounds, auditory icons, arbitrary environmental sounds, and speech for a number of in-vehicle alerts, including low fuel, door ajar, and low tire pressure. Accuracy was best, near ceiling, and comparable for speech and auditory icons; arbitrary environmental sounds trailed and abstract sounds offered particularly poor accuracy. Speech and auditory icons also showed the fastest response times. This application of auditory icons and perhaps spearcons is yet another easily implemented improvement compared with the default tones that alert vehicle operators to conditions such as low fuel and other maintenance problems.

Given the potential for sounds to saturate a driving environment, alerts should probably sound only once for noncritical, non-safety-related events. Such alerts also might be repeated once, for example, when starting the vehicle, but the frequent repetition of alerts that do not require immediate action have a real potential to distract the driver from both the driving task and from more critical alerts regarding collisions and other safety-related hazards.

Energy Conservation Systems

A recent study (Manser, Rakauskas, Graving, & Jenness, 2010) examined a number of visual displays in the instrument panel for providing the driver both instantaneous and summative information about fuel economy. This Fuel Economy Driver Interface Concept (FEDIC) has been proposed as an in-vehicle information display to promote driving practices that preserve fuel economy and promote wiser energy consumption while driving. One of the more successful displays prototyped in the study involved a horizontal bar that lengthened as instantaneous fuel economy became more efficient. During periods of hard acceleration, for example, the display could provide continuous feedback about fuel consumption and potentially mitigate fuel waste. A potential problem with a visual display in a fuel economy task, however, is that periods of hard acceleration are exactly the time during which the driver is best served by keeping visual attention focused on the road rather than glancing at the instrument panel.

Given that the FEDIC displays quantitative data, sonification of the immediate fuel economy may affect positive change on drivers' fuel economy–related behaviors. Three crucial concerns for the design of sonifications are mappings, scalings, and polarities (Walker, 2002, 2007). Mapping refers to the designer's decision regarding which acoustic parameter to use to represent changes in a referent conceptual data dimension. The designer must also choose how to scale the changes in the sound parameter as a function of data parameters. Finally, the designer must consider polarity, which is whether increases in the acoustic parameter correspond to increases or decreases in the data. Listener groups do have systematic and fairly consistent intuitions about the correct mapping, scaling, and polarity for representing a given conceptual data dimension with sound (see Walker, 2002, 2007). For FEDIC systems, mapping fuel efficiency to pitch represents one obvious mapping choice, but an empirical investigation could determine the best mapping, scaling, and polarity for an in-vehicle FEDIC auditory display.

An ongoing, continuous sonification of fuel economy information could become annoying or distracting for drivers, so the driver might be best served by an interface that delivers more brief and intermittent messages. Edworthy et al. (2004) designed *trendsons*—trend monitoring sounds for operational variables in helicopters, such as rotor overspeed and rotor underspeed. The sounds were designed to function as a sort of warning-sonification hybrid. Trendson sounds in IVTs could carry additional information (relative to a traditional warning) about vehicle fuel economy data that ideally not only warns the driver but also guides the driver toward rapid corrective action.

Emerging Driver State-Awareness Systems

A variety of emerging technologies are being refined with the goal of using alerts to intervene and influence driver behaviors as a function of mood and other states that may negatively affect driving performance. For example, systems have been developed to detect driver fatigue (Heitmann, Guttkuhn, Aguirre, Trutschel, & Moore-Ede, 2001). To the extent that an IVT can detect driver fatigue, alerts can be implemented to facilitate the driver's awareness of his or her own exhausted state. Similarly, researchers (e.g., Lisetti & Nasoz, 2005) are beginning to consider the potential for systems to diagnose drivers' emotional states, such as anger or distress; a series of prompts or alerts might be able to assist the driver in stressful driving situations or to mitigate road rage. The literature on this topic to date has been much more focused on the problem of detecting driver states, however, and little attention has been paid to the design of the alerts for the system. The appropriate use of alerts will most likely include a prominent auditory component, but more research will be needed to determine the best sounds to improve driving performance as a function of the driver's internal conditions.

AUDITORY DISPLAYS FOR INTERACTING WITH IN-VEHICLE INFOTAINMENT SYSTEMS

The human factors difficulties with in-vehicle information and entertainment systems are largely menu and selection based. A driver (or passenger) may have a list of possible destinations, points of interest, contacts, or audio and video entertainment options, and he or she must locate and select the desired menu option quickly, with little use of the eyes, and with minimal cognitive distraction.

Auditory menus have been examined in some detail in recent years, and researchers have had success with designing auditory menus that may work well for IVIS. A simulated in-vehicle system that incorporated auditory menus with manual interaction for tasks such as composing text messages, changing system settings, making phone calls, deleting messages, and playing songs was shown to result in safer driving performance and lower perceived workload than a visual interface for all tasks, although the composition of messages with the auditory menus was considerably slower than with the visual interface (Sodnik, Dicke, Tomazic, & Billinghurst, 2008).

Brewster (1998) conducted a series of studies that showed that participants with minimal training could identify hierarchical menu positions with 81.5% accuracy after hearing a hierarchical earcon and with 97% accuracy after hearing a compound earcon. The hierarchical earcons used timbre, register, rhythm, and tempo to represent the hierarchy, whereby each sublimb assumed the properties of each of its parent limbs plus one new, unique acoustic property. The compound earcons simply created a motif for the numbers 1 through 9 and represented members of the hierarchy in a book chapter format (e.g., "1.1.2") that had to be translated by the listener to a location in the hierarchy.

A potential problem with earcons for IVIS, however, is learnability. Abstract sounds, such as earcons, have been repeatedly shown to be difficult to learn and remember. Furthermore, the content displayed in IVIS may feature extensive catalogs (e.g., of contacts, songs, videos, waypoints, or destinations) that will further complicate the use of earcons by requiring large catalogs of abstract sounds. Auditory icons will also be problematic. Consider a list of contacts, for example. Will the user have a different auditory icon for each contact in his or her electronic phone book? This approach may be tenable for a limited number of menu items but not for an extensive catalog. Spearcons, however, combine the flexibility and brevity of earcons with the existing knowledge of the meaning of speech phrases.

In empirical investigations, spearcons were better than earcons or auditory icons and as good as speech for menu navigation (Walker et al., 2006), and another study showed that spearcons were learned considerably faster than earcons for a set of menu items representative of the complexity of a mobile device menu structure (Palladino & Walker, 2007). Spearcons may be used in combination with conventional TTS to enhance the speed of auditory menu navigation. Palladino and Walker (2008) compared auditory, TTS-only menus with the same menu items presented as a spearcon followed by TTS. The spearcon-enhanced menu supported both rapid and slow navigation through menus. In that study, the spearcon-plus-TTS condition resulted in a reduced time to target as users searched for menu items within a 2-dimensional menu structure, and the enhanced search time became more pronounced as users searched for items deeper within the menu structure. The spindex enhancement was also shown to improve search times in auditory menus, particularly for menus with long lists of items (Jeon & Walker, in press).

A follow-up study (Jeon, Davison, Nees, Wilson, & Walker, 2009) was geared toward the use of enhanced auditory menus for menu navigation with IVTs in the presence of a visual primary task. Results showed that TTS, spearcons, spindex, and various combinations of spearcons and spindex with TTS all improved performance compared with a visual-only condition on the menu navigation task, which required participants to select an item from a long list of songs. All audio conditions also allowed for better performance of the concurrent visual task—a demanding, continuous visuomotor task—and reduced subjective workload as compared with the visual-only condition.

Furthermore, users overwhelming preferred both the spindex-plus-TTS combination and the spindex-plus-spearcon-plus-TTS combination. Enhanced auditory menus that present combinations of spindex or spearcons prepended to speech representations of menu items have the potential to greatly improve safety in the auditory navigation of menus in IVTs, as reduced time to target and reduced workload in interacting with IVTs translate to more time and mental resources for attending to the primary task of driving.

IVTs for Communication

Technology has increasingly allowed for constant, instantaneous communication via phones and various text delivery technologies, including e-mail and mobile social networking. These technologies have provided for convenient connectivity, but they have also presented considerable threats to safe driving. A number of studies have shown that even hands-free cell phone use during driving caused considerable decreases in driving performance (e.g., Horberry et al., 2006; Strayer & Drews, 2004), and this impairment has been explicitly linked to decreases in visual attention during hands-free conversations (Strayer, Drews, & Johnston, 2003; also see McCarley et al., 2004). Strayer and Drews (2004) found that conversations negatively affected the driving performance of both older and younger adults, and the addition of a conversation led younger adults to respond as slowly as older adults' baseline, driving-only response times.

Similarly, the detrimental impact of text messaging while driving has been documented empirically (Drews, Yazdani, Godfrey, Cooper, & Strayer, 2009; Hosking, Young, & Regan, 2009) and has resulted in aggressive public awareness campaigns against texting while driving (e.g., http://texting-while-driving.org/). Nonetheless, research (e.g., Lerner, Singer, & Huey, 2008) has suggested that the desire to phone or send text messages while driving will likely outweigh the potential risks associated with the tasks, especially for younger drivers. Given that drivers are almost certain to continue using communication systems in the car, human factors and system designers should work to build systems that allow for drivers to accomplish communications tasks as safely as possible. IVTs that feature auditory displays may be able to mitigate some of the safety issues associated with in-vehicle communications.

Cell phone conversations. Research (Drews, Pasupathi, & Strayer, 2008) has shown that a cell phone conversation is different from and more harmful to driving performance than a conversation with a passenger, because conversations with passengers often involved traffic-related tangents that likely improved awareness of the driving context. Conversations with passengers also adapted to the demands of the driving situations. Other researchers (Nunes & Recarte, 2002), however, have argued that cell conversations and live conversations are no different per se; rather, the complexity of the conversation content determines the potential for driver distraction. These views are more or less compatible in that the attenuation of distraction when talking to a passenger seems to be contingent on the passenger's active attention and appropriate responses to the driving situation.

Both easy and difficult conversations resulted in the same increase in subjective workload compared with a control condition in one study, however, and both types of conversations adversely affected driving performance (Rakauskas, Gugerty, & Ward, 2004). The effects of producing language (speaking) and comprehending (listening) each produced about the same level of impairment in driving performance (Kubose et al., 2005). In another study (McCarley et al., 2004), however, researchers found that simply listening to others' conversations for comprehension did little to impair visual change detection in traffic scenes, whereas participating in a conversation did impair visual attention to change. Thus, the distracting effects of speech comprehension on driving seem to be unique to the driver's participation in the conversation rather than a function of listening per se.

Auditory displays offer the only feasible modality solution for interacting with a cell phone while driving, yet clearly, much more work needs to be done to mitigate the potential for even hands-free cell phone conversations to adversely affect driving performance. Findings from a study (Shinar & Tractinsky, 2004) suggested that over time, younger and middle-aged adults can learn to manage the cognitive demands of hands-free phone use while driving such that the negative effects of phone conversations on some driving performance variables decreased, so training and safe practice in the strategic management of in-vehicle phone conversations may be helpful. Research to date also has suggested that the best way to reduce distraction from phone conversations in the vehicle may be to reduce the complexity of the conversations, and one possible solution could be to engineer context-aware systems that help to strategically control the flow and delivery of conversation audio on the basis of driving demands.

In-vehicle e-mail, text messaging, and social networking. Wireless technologies have begun to allow for the delivery of e-mail and text-based messages in vehicles, and receiving and composing e-mail while driving will need to be accomplished without using the eyes to read extensive amounts of text or using the hands to type. Lee, Caven, Haake, and Brown (2001) examined the effects of an auditory and voice-based in-vehicle e-mail system on driving performance. The system used TTS to read messages aloud to the driver, and a simulated voice recognition system was used to compose e-mails from the driver's speech. When a lead vehicle began to brake, drivers responded (released the accelerator) 30% slower when using the e-mail system as compared with a control condition.

The effects on driving of a complex e-mail system (with up to seven suboptions for each of three primary menu nodes) and a simple e-mail system (with only two suboptions for each primary menu node) were equivalent, although drivers were significantly better at understanding the contents of e-mail messages with the simple system. Drivers' perceived workload increased when using the e-mail system as compared with the control condition, and the complex system resulted in higher perceived workload than the simple system. This study demonstrated that removing the visual and manual requirements of in-vehicle e-mail will not fully mitigate the potential for increased cognitive workload and driver distraction to impede safe vehicle operation. As such, IVT designers may need to find ways to reduce both the length and complexity of e-mail messages delivered to the driver while preserving the intended meaning and relevant aspects of the message.

Temporal aspects of message delivery may also be important for in-vehicle e-mail systems. A study (Jamson, Westerman, Hockey, & Carsten, 2004) examined how the timing of e-mail delivery affected driving performance. In one condition, a chime alerted the driver to an incoming message, and the system automatically began to read the message to the driver. A second condition also alerted the driver to message arrivals with a chime, but it required the driver to manually initiate the delivery of the message via a button on the steering wheel. E-mail messages required true-or-false responses, which were also made via buttons mounted on the steering wheel. Drivers responded to the e-mail questions faster in the system-initiated message condition, and results suggested that participants in the driver-initiated message condition strategically deferred message retrieval during more-demanding driving scenarios. The safety margin for a time-to-collision measure was reduced by half when drivers were using the e-mail system as compared with a baseline control measure, regardless of the type of e-mail system used.

Drivers in the study attempted to compensate for the effects of the e-mail task on driving by slowing down and allowing for more headway between lead vehicles. The researchers found an interesting interaction such that anticipatory braking was worse with the system-initiated messages during times when an e-mail was being read, but this effect reversed such that anticipatory braking during times when no e-mail was being read were better with the system-initiated messages. The researchers suggested that the driver-initiated system introduced an additional scheduling task that was not required with the system-initiated messages. This finding highlights the challenges in understanding the effects of combining a cognitively complex task, such as e-mailing, with a dynamic, demanding task, such as driving, as the effects of using in-vehicle communications systems will be different in various driving scenarios.

Finally, the spatial location within the vehicle from which the audio emanates should be considered in the design of in-vehicle communications systems. A study conducted by Spence and Read (2003) showed a pronounced decrement in performance for speech shadowing while driving when the speech was presented from the side of the vehicle rather than from in front of the driver. The position of the speech had no impact on driving performance, but the authors suggested the shadowing impairment resulted when the drivers divided spatial attention between the driving task (looking straight ahead) and the speech location in the side presentation condition. This finding suggests that the presentation of in-vehicle communications from a location where the driver's visual attention is directed at the front of the vehicle may improve the comprehension of the messages being delivered and thereby, importantly, reduce the complexity associated with processing verbal messages while driving.

Verbal displays and concurrent in-vehicle conversation or music. An interesting line of work has examined the extent to which the presence of various common sounds interferes with concurrent verbal working memory tasks, such as remembering words and numbers. Verbal working memory is clearly a major cognitive element of interacting with communication systems in IVTs. Unattended (i.e., to-be-ignored) noise does not interfere with concurrent verbal working memory tasks, but unattended speech does (Salame & Baddeley, 1987). Instrumental and vocal music were both also disruptive to verbal working memory tasks, but instrumental music caused less interference than did vocal music (Salame & Baddeley, 1989). Interestingly, instrumental music that is associated with lyrical content has been shown to be considerably more disruptive to verbal working memory than is purely instrumental music, even when the verbal lyrics are omitted from the stimulus (Pring & Walker, 1994).

These findings strongly suggest that sounds interfere with verbal working memory to the extent that the sounds possess and are encoded according to verbal labels, and auditory-display users have been shown to sometimes use verbal labeling strategies for sounds (Nees & Walker, 2008b). In another study, long speech messages were found to interfere with a concurrent verbal memory task, whereas brief verbal keywords, auditory icons, and earcons were not disruptive (Vilimek & Hempel, 2005; also see Bonebright &

Nees, 2009). In general, longer speech messages from e-mail, text messaging, or in-vehicle social networking could be expected to interfere with concurrent conversation, and concurrent, especially lyrical music will likely have some detrimental impact on the comprehension of verbal messages from in-vehicle communication systems.

Auditory Displays That Aid Navigation

Global Positioning System (GPS) navigation systems are well on their way to becoming a standard tool in passenger vehicles. GPS systems typically use speech output to give simple navigation instructions (e.g., "Turn left in 200 feet"). Some research has suggested that the lateralized presentation of auditory navigation instructions in which the sounds emanate from the direction of a prescribed turn direction (left or right) may improve driver performance with the system (Lee, 2010). Some navigation systems also use simple beeps or tones to indicate when a verbal message is arriving (Llaneras & Singer, 2002). The purpose of these sounds is to capture attention and prepare the system operator for the delivery of a verbal message. Tones may be appropriate in these systems as a preparatory signal, as they may be more likely than speech to be heard over concurrent conversation in the vehicle.

Little research to date has examined the effects of the type of preparatory sound on both navigation performance and the primary driving task, and more empirical evaluations of the best design for the delivery of audio navigation instructions are needed. More-complex sounds, such as auditory icons, earcons, or spearcons, may be more effective and informative regarding the type of navigation message to be delivered as compared with the generic tones that dominate current systems.

In general, current in-vehicle GPS navigation systems are lacking in their ability to provide information landmarks. Points of interest and notable buildings or structures can help to aid navigation (for a review, see Burnett, 2000) and are a common feature in informal person-to-person navigation directions. The inclusion of auditory displays for landmarks in vehicle navigation systems, however, will need to be subtle enough to avoid unwanted distraction for the driver. Verbal auditory landmarks already have been shown to improve navigation performance without introducing unwanted complexity to the driving task (Reagan & Baldwin, 2006). Auditory icons or spearcons may also be able to convey information about points of interest and other landmarks that may be beneficial and informative during in-vehicle navigation (see Dingler, Lindsay, & Walker, 2008).

Summary of Current Uses of Sound in Vehicles

Existing information displays in vehicles have incorporated auditory displays with some success. Current systems use sound to provide alerts and warnings, and IVIS and navigation systems have used auditory displays to alleviate at least some of the need to look at visual displays while interacting with these systems. Designers have intuitively recognized the need to limit the use of visual displays during driving. These developments notwithstanding, the full potential of auditory displays in vehicle cockpits has yet to be realized. To date, most systems continue to default to beeps, tones, and chimes for auditory information display, despite a growing empirical literature to suggest that more informative sounds, such as auditory icons, spearcons, and possibly earcons, enhance the effectiveness and safety of many in-vehicle systems. Research and design challenges with auditory displays for IVTs remain to be solved, and ultimately, the best systems will address a multitude of human factors issues with sound in vehicles.

HUMAN FACTORS CONSIDERATIONS WITH AUDITORY DISPLAYS FOR IVTS

A number of fundamental topics within the domain of human factors research and practice are relevant to the use of sound in IVTs. The refinement of best practices for implementing IVTs will be informed by research and theory related to multitasking, situation awareness, training, workload, and cognitive aging. In turn, effective display designs for IVTs will also advance theory and research on these important human factors topics.

Distraction and Multitasking

A naturalistic study of driving that was conducted before IVTs became prevalent revealed that numerous sources of in-vehicle driver distraction already existed (Stutts et al., 2005). In that study, for example, participants who listened to the radio adjusted its controls 7.8 times per hour of driving on average, for an average of 5.5 s each time. Researchers have recommended that no glances at IVTs should exceed 2 s, and glances should be no more than 1.2 s on average (for a review, see Burns & Lansdown, 2000). Brief glances (less than 2 s) away from the road have negligible impact on driving performance, but longer glances result in dramatic increases in accident risk (Klauss et al., 2006).

Distractions from IVTs can result in impaired or altered responses to critical driving events that adversely affect safety (Hancock, Simmons, Hashemi, Howarth, & Ranney, 1999). For example, people have a longer latency to respond to potential pedestrian driving hazards when interacting with an IVT (Lee, Lee, & Ng Boyle, 2009). A study showed that the effect of listening to either music from a radio or the audio track from a movie (such as when a backseat passenger is using an in-vehicle entertainment system) had negligible impacts on driving performance (Hatfield & Chamberlain, 2008), however, which suggested that some in-vehicle entertainment that requires no action of or attention from the driver will not negatively affect driving. IVTs that demand attention from the driver or require driver interaction with displays and controls, on the other hand, can present considerable difficulties with respect to distraction.

Given that interactions that involved controlling a less complex system (a radio) took more than 5 s (Stutts et al., 2005), the development of a safe interface for IVTs—in which information display will be appreciably more complex than a traditional radio—represents an especially challenging design problem for human factors practitioners. Driving is a multitasking scenario that requires the integration of multiple pieces of information from the visual, auditory, and possibly, tactile modalities. An important question, then, is to what extent do auditory displays interfere with concurrent tasks or information processing? And to what extent do concurrent tasks interfere with the presentation of information via auditory displays?

The underpinnings of dual-task interference are an especially thorny theoretical topic. A variety of models of the human as an information processor have been proposed, and each attributes dual-task interference to different limitations in the human's ability to process simultaneous information and execute concurrent tasks. One model that has been frequently offered as theoretical motivation in the auditory display literature is multiple resources theory (MRT; e.g., Wickens, 2002). The theory, discussed next in a simplified form, describes human information processing in stages, including stimulus modalities, processing codes, and response modalities. At each stage, a dichotomous pool of resources serves as a metaphor for the human capacity to process information successfully.

The stimulus modalities stage features the dichotomy between vision and audition. Processing codes in working memory are verbal or visuospatial, and response modalities are vocal or manual. Tasks that require the same member of a dichotomy at any stage compete for resources, and resource competition results in decrements in performance in one or both of the tasks to the extent that the available resources are overextended. The key attributes of resources are divisibility—resources can be divided across tasks—and allocatibility—resources can be strategically divided such that the more difficult tasks receive a disproportionate share of available resources.

The auditory display literature has often drawn from only the stimulus modalities dimension of MRT (Wickens, 2002), sometimes without regard for the rest of the theory or acknowledgment of other possible models of dual-task interference. An argument that we call the "separation-by-modalities argument" cites the stimulus modalities dimension of MRT and states that dividing information between vision and audition will be beneficial to the system operator. The separation of information presentation across modalities is often beneficial, but the other dimensions of MRT (such as the processing code and the response modality) must also be considered. In some cases, the appropriateness of a resource model altogether must also be a matter of concern (Navon, 1984). Important consequences for auditory interface design hinge on whether the human information-processing system operates with general (single) or differentiated (i.e., the *multiple* in *multiple resources*) limitations and whether those limitations behave as all-or-none processors or as divisible, allocatable resources.

For example, findings from one study (Bonnel & Hafter, 1998) suggested that stimulus detection was not harmed by competing auditory and visual stimuli, but stimulus identification suffered in competing auditory-visual stimuli scenarios. Dell'Acqua and Jolicoeur (2000) found that an auditory tone judgment task interfered with a task requiring the classification of abstract visual matrices, and performance on the two tasks seemed to deteriorate concurrently from trial to trial (i.e., there was no trade-off observed). Findings such as these are common in the literature and somewhat difficult to reconcile with the predictions of the stimulus modalities dimension of multiple resources, at least from the simple viewpoint of the separation-by-modalities heuristic.

Auditory interface researchers and designers should be aware of the value of the separation-by-modalities heuristic, but they should also be aware of the assumptions inherent in this perspective, the other dimensions of MRT, and the existence of difference perspectives on dual-task interference altogether. For example, a general resource model (e.g., Kahneman, 1973) of dual-task interference (without "multiple" divisions) would predict dual-task interference as the result of the overall combined difficulty of tasks, regardless of their modality or content. At least one study (Merat & Jamson, 2008) has provided data to suggest that general resource models best explained the performance of detection tasks during driving while interacting with IVTs.

With a general resource model, the separation of information to different perceptual modalities is more or less inconsequential. This perspective is clearly inadequate to account for much of the existing multimodal, multitasking data (see, e.g., McLeod, 1977). The point, however, is that no single existing model of multitasking performance can adequately predict the best-practice distribution of tasks across modalities, thus an awareness of the possible models of interference is required and should guide research and design.

Situation Awareness

Situation awareness involves perceiving and understanding relevant information of a system and the environment as it relates to the current state of the system, the goals of the system operator, and the potential future states of the system (Endsley, 1995). When situation awareness decreases during driving, the potential for accidents increases. A study (Lerner et al., 2008) showed that people are generally willing to engage in cell phone use across and without particular regard for a number of different driving scenarios. The decision to engage or not to engage in potentially distracting activities during driving was motivated by the desire to accomplish the secondary activity rather than by concern for driving conditions. Drivers seemed to perceive minimal risk in using a cell phone while driving, although they were less willing to use navigation systems and personal digital devices.

The results of the study also suggested that drivers showed little awareness or anticipation of upcoming road conditions when deciding whether to engage in a distracting in-vehicle activity, and they also did little preparation before driving (e.g., strategically locating devices) to mitigate the demands of distracting activities that might be undertaken while driving. Of the age groups examined in the study, teenagers perceived the least amount of risk in undertaking distracting activities while driving, and they also had overly optimistic assessments of their own multitasking abilities.

These findings (Lerner et al., 2008) suggested an alarming lack of situation awareness in drivers' decisions to engage in potentially distracting tasks while driving. IVTs and auditory displays could potentially help to sustain situation awareness during driving. Visual feedback based on eye tracking data has been shown to prompt drivers to spend less time with their eyes away from the road to look at the visual display of an IVIS (Donmez et al., 2007), and audition may offer another medium to alert drivers to refocus vision in driving- and situation-appropriate ways.

Results of a recent study (Davidse, Hagenzieker, van Wolffelaar, & Brouwer, 2009) suggested that advanced driver assistance systems (ADAS) that delivered information (through verbal auditory instructions) to drivers about upcoming intersection rights-of-way, view obstructions, and gaps in traffic as well as alerts about one-way streets facilitated safer driving for both younger and older drivers. Although ADAS such as this are not currently available, they are not far-fetched, and one can imagine that refinements to existing sensing, location, and information technologies could soon make such ADAS common.

Training

To the extent possible, auditory interfaces should be designed in a way that offers intuitive understanding to the listener (see, e.g., Gaver, 1993) and minimizes the need for excessive training, which listeners may be unwilling to complete. In a study of one IVT, for example, most people learned to use the system from reading the owner's manual or through trial and error while driving (Jenness et al., 2008). Notwithstanding this consideration, auditory interfaces generally entail a novel experience for the user, and some period of training for and acclimation to the interface is to be expected. Very brief training has been shown to facilitate performance with auditory displays for a variety of tasks (Loeb & Fitch, 2002; Smith & Walker, 2005; Walker & Nees, 2005).

Although performance over time has not often been reported in one-shot auditory interface studies, some studies that have reported performance data across trials or blocks of trials have found substantial performance improvements over time (Bonebright & Nees, 2009; Jeon et al., 2009; Nees & Walker, 2008a; Walker & Lindsay, 2006b). Whereas warnings, for example, should require little or no training to understand, users might be more willing to spend time practicing and training with auditory interfaces for IVIS purposes when the interfaces add value within a system. Still, to the extent possible, interfaces should be designed to require the minimum amount of training possible to accomplish the system tasks successfully.

Auditory Interfaces and Workload

Workload may be conceived of as the demand imposed on an operator while accomplishing a task or tasks, and performance breaks down with high workload (see, e.g., Wickens, 2002). Much has been made of the potential for sound to reduce the workload of interacting with a system, particularly in cases such as driving, in which the system imposes high demand on the visual system. In general, research has shown that the addition of auditory cues to interfaces or the substitution of auditory displays for one of two visual displays in multitasking scenarios does indeed reduce perceived workload (Brewster, 1997; Brewster & Crease, 1999; Brewster & Murray, 2000; Brewster, Wright, & Edward, 1994; Jeon et al., 2009). Some caveats to this general finding also have been discovered. Perceived workload seems to increase as the number of concurrently presented sounds in the interface increases (e.g., for one or two concurrent earcons as compared with four, see McGookin & Brewster, 2004).

A recent study compared visual and auditory warnings with either natural or symbolic mappings and high- and low-workload manipulations. Natural mappings, such as those characteristic of auditory icons, resulted in better accuracy for both visual and auditory warnings, but the natural mappings resulted in significantly faster response times only for auditory warnings with high workload (Stevens, Brennan, Petocz, &

Howell, 2009). In another study (Baldwin, 2002), speech displays were more effective when louder but only in high-workload conditions. More research is needed to understand how workload conditions affect and are affected by the use of IVTs, but research has generally supported the heuristic that auditory displays are more workload-appropriate than visual displays for IVTs.

The most common metric of mental workload is the NASA–Task Load Index (NASA-TLX; Hart, 2006; Hart & Staveland, 1988). The NASA-TLX features an overall index of mental workload as well as subscales for mental, physical, temporal, effort, frustration, and performance demand. Although inquiries have been made into the development of a measure of auditory workload (Rench, 2000), no tools currently exist for quantifying modality-specific workload. A related and interesting theoretical dilemma is presented by the pervasiveness of MRT (see, e.g., Wickens, 2002) as a justification for auditory displays and the reduction of *visual* workload. If the auditory and visual modalities act as independent resources, then modality-specific workload measures would be useful and indeed required to assess the impact of auditory interfaces on multimodal multitasking. If, however, limitations in information processing are predicted by the overall general workload demands of combined tasks, irrespective of their modality, then a general workload measure, such as the NASA-TLX, likely captures workload-related variability, and the constructs of modality-specific auditory and visual workload become unnecessary.

The NASA-TLX as it currently exists has been used to compare the workload demands for auditory and visual tasks in isolation with multimodal dual-task workload demands. At this point in time, the utility of a modality-specific measure of auditory workload remains unclear.

Multimodality

This review has made a case for the role of the auditory modality as an important contributor to effective information display for IVTs, but we do not intend to suggest that sound offers the only medium that should be considered in the design of IVTs. Future vehicles will be equipped to present information in visual, auditory, tactile, and perhaps even olfactory forms, and the best system for effective IVTs that preserve and enhance safe driving will adopt an empirically informed, modality-appropriate approach to information display. Spence and Ho (2008b) recently commented on issues of multimodality in vehicle interface design and concluded that multimodal displays (audiovisual or audiotactile) may ultimately prove to be the most effective design approach, particularly for an aging population of drivers.

Results of a study (Navarro, Mars, & Hoc, 2007) suggested that for lane departures, motor priming for corrective action from steering wheel vibrations (i.e., a mild movement of the steering wheel in the corrective direction) was more effective than lateralized auditory warnings or vibrotactile warnings, although all conditions improved driving performance. Multimodal presentations achieved by adding sound to either of the other conditions showed no additive improvement in performance. Scott and Gray (2008) found that tactile warnings were significantly better than visual warnings for improving reaction times to potential rear-end collisions, and no significant differences were found between visual and auditory or between auditory and tactile warnings. These results suggested that the haptic modality represents a potentially strong candidate for in-vehicle warning presentation. Nearly 40% of participants in the study found the tactile warnings to be unpleasant, however, which led the researcher to speculate that participants were responding quickly in an effort to terminate the sensation of the tactile warnings.

In another study (Mohebbi, Gray, & Tan, 2009), tactile warnings for potential rear-end collisions were found to be more effective than auditory warnings for drivers involved in either simple or complex cell phone conversations while driving, although the auditory warning they used was a simple tone that has been shown to be less effective than other potential sounds, such as auditory icons.

More research is needed to understand when tactile displays are superior to auditory or visual displays for the effective display of information as well as for increasing the driver's subjective satisfaction with the display. Multimodal displays should be implemented consistently within an IVT system, however, as research (for a review, see Spence & Driver, 1997) has suggested that a range of tasks, including detection, feature discrimination, and localization of a stimulus, are degraded when a stimulus occurs in an unexpected modality. Thus, system designers should not alternate the signal for the same message or warning between modalities within a given task scenario.

Older Drivers

Aging results in a decline in audition that is characterized by shifts in thresholds for adults, especially for higher-frequency sounds (Gelfand, 2009). Aging can result in negative shifts in older adults' abilities to discriminate the frequencies and durations of sounds (Abel, Krever, & Alberti, 1990) and also the gaps between sounds (Schneider & Hamstra, 1999), even without hearing loss per se. In another study, older adults were slower than younger adults to match nonspeech environmental sounds with their visual representations (Saygin, Dick, & Bates, 2005), although findings such as these may be attributable to processes involved with responding rather than to auditory perception (see, e.g., Alain, Ogawa, & Woods, 1996).

In general, hearing loss or normal deficits associated with aging and other declines (e.g., in response time) need to be considered when designing auditory displays for older adults (see Baldwin, 2002). The intensity of sounds may need to be increased to accommodate older adults, and this minor accommodation may be very worthwhile. Several studies have suggested that IVTs that aid safe driving offered especially pronounced driving improvements for older adults. Baldwin and May (2006) showed that auditory warnings in a simulated driving scenario with high collision risk showed more pronounced reductions in collisions for older adults as compared with younger adults, although the system reduced crashes for all users.

Auditory Displays, IVTs, and Human Factors

The human factors issues regarding the design and implementation of auditory displays in IVTs present a wealth of challenges and opportunities for researchers and system designers. Questions about the effective use of sound in vehicles are enveloped by many of the most fundamental issues in human factors. To successfully meet the challenge of designing safe auditory and multimodal vehicle interfaces, researchers and designers will both draw from and contribute to our general understanding of effective human-machine systems.

OBSTACLES, CHALLENGES, AND RESEARCH NEEDS

The lack of a theoretically informed framework in which auditory interface research can grow has been and likely will continue to be a major obstacle to future breakthroughs. Contributions to the literature informing auditory interface design have come from a diverse array of fields, including engineering, computer science, psychology, audiology, and music. The field benefits greatly from interdisciplinary insights, but the multiplicity of approaches has presented obstacles for establishing a shared base of knowledge. To advance the best-practice use of auditory interfaces, auditory interface researchers must establish coherent theoretical frameworks that effectively organize extant data. Auditory interface design to date has sometimes been accomplished in a theoretical vacuum and without awareness of existing designs. This dilemma emphasizes the need for researchers to disseminate knowledge effectively and also the need for researchers and practitioners to perform due diligence in knowing and searching the relevant corpuses of literature.

Any cohesive theoretical approach to auditory interface design must use strong ties to the literature on auditory attention, working memory, and other human auditory capabilities and limitations to identify the appropriate situations in which sound interfaces will best accomplish the tasks and goals of the system. Indeed, the modality appropriateness of information displays has yet to be fully articulated across modalities and design scenarios. Currently, the most used heuristic for choosing modality-appropriate displays seems to be the separation-by-modalities argument, which simply advocates for dividing information between the eyes and ears, yet this heuristic cannot guide modality-appropriate interface design in all scenarios. More research is needed to inform more-precise design heuristics for modality appropriateness.

The promising role of intelligent systems in automation of modality-appropriate displays in a given context (see, e.g., Brooks & Rakotonirainy, 2007) or modulation of acoustic variables (intensity, frequency, etc.) as a function of concurrent sound contexts (Antin, Lauretta, & Wolf, 1991; Peryer et al., 2010) has only begun to be explored. Engineering has provided sensors that can actively monitor a variety of system states (e.g., noise, concurrent speech, operator states) relevant to the output of auditory interfaces. To the extent that information from sensors can be integrated, auditory interfaces may be able to actively adjust to a given context or set of operating constraints. Intelligent systems that limit the flow of information during critical driving moments or that actively adjust or attenuate acoustic signals in auditory interfaces (e.g., Peryer et al., 2010) may be possible and part of a greater solution for safe IVTs.

Researchers (Brooks, Rakotonirainy, & Maire, 2005) have even begun to investigate intelligent algorithms that use Bayesian logic to more precisely identify and ameliorate sources of distraction in specific driving situations. Unfortunately, the corresponding knowledge in auditory display design that will be required to take advantage of such systems is lacking. More research is needed to determine the best-practice presentation of alarms or sonifications in noise, for example, or the type of sound that most efficiently promotes correct courses of action when a system operator is under duress.

Another major concern for auditory interface design involves the synergy between research on fundamental psychoacoustic, attentional, perceptual, and cognitive functions of the auditory system and the successful translation of this research into auditory interface design. The sheer bulk of the scientific literature is overwhelming and growing, and it seems like much (or at least some) of the usable extant knowledge from psychoacoustics and other fields has yet to be effectively mined and translated into useful knowledge for auditory interface design. Auditory interface researchers must strike a balance that recognizes the importance and relevance of insights from laboratory studies of basic auditory and cognitive-perceptual functions while recognizing that the results of studies that inform auditory interface design do not provide strict guidelines for a given design scenario (Watson & Kidd, 1994).

Data from controlled laboratory settings should serve as starting point for auditory interface design rather than an end point. The review and integration of laboratory data will help to inform the early design process and to identify auditory interface design candidates to advance to iterative design phases, which must include testing and evaluation of designs with representative samples of users in representative system conditions.

The most effective approach to auditory interface design not only will consider acoustics or auditory perception but will consider all of the relevant acoustic and psychosocial variables issues *within the context of a human- and system-oriented design process* (see, e.g., Watson & Sanderson, 2007). Figure 2.2 summarizes one conceptualization of what such an iterative design process entails. Whenever possible in the process, decisions should be made on the basis of sound empirical evidence or data rather than ad hoc solutions or idiosyncratic assumptions. Through iterative designs that are evaluated and refined via a process, the human factors practitioner will ultimately implement a design that is usable, safe, and aesthetically desirable. Finally, successful designs will result in reusable knowledge, theory, and eventually, standards that inform the best-practice use of auditory displays for IVTs.

CONCLUSION: ANTICIPATING THE SOUND OF THE VEHICLE COCKPIT OF THE FUTURE

Auditory display design is arguably on the cusp of a paradigm shift whereby researchers begin to design to the advantages of the auditory system more directly. Many early attempts at auditory interfaces sought to build auditory versions of visual interfaces. This design approach places auditory interfaces in the disadvantaged position of being twice removed from the data or information that the interface intends to communicate (Frauenberger & Stockman, 2006). Recently, researchers have begun to discuss and recognize the flaws in trying to make visual interfaces into auditory interfaces versus the more productive approach of trying to build the underlying information and data directly into auditory interfaces (Jeon, 2010).

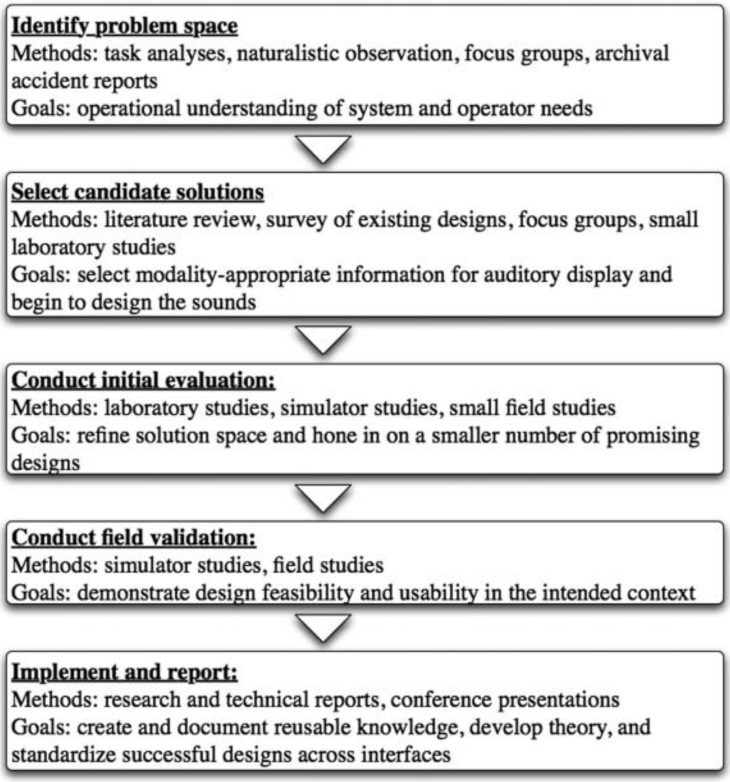

Figure 2.2. *An iterative process for designing auditory displays for in-vehicle technologies.*

The temporal sensitivity and acuity of the auditory system is one of its primary strengths; thus, truly auditory interfaces of the future will likely involve designs that optimize the presentation of sounds in time. This type of approach will probably minimize the number of concurrently presented sounds in favor of rapid sequential presentation of sounds. Such an approach to auditory display design will be at least partly driven by innovations and needs in the IVT domain, and auditory displays will in turn contribute much to the design of safe and effective interfaces in vehicles. The IVT is a compelling use case for auditory interfaces, as the adverse consequences of an interface that relies on vision in a vehicle can be catastrophic. Auditory and multimodal displays may be able to solve many of the problems posed by visual interfaces in the vehicle.

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