Factors in the Design of Effective Auditory Displays

Charles S. Watson and Gary R. Kidd
Department of Speech and Hearing Sciences
Indiana University
Bloomington, IN 47405
Email: watson@indiana.edu, kidd@indiana.edu

Abstract

The design of effective auditory displays requires an understanding of both capabilities and response proclivities. This distinction is explained in relation to a variety of auditory tasks and a range of acoustic stimuli. Factors that are important in the assessment of auditory processing, such as the type of task, amount of training, and the complexity of the sounds, are discussed in the context of several studies of the perception of complex sounds. It is suggested that auditory science provides many answers to questions about auditory capabilities and proclivities, and at least a few useful principles for the design of effective auditory displays.

1 Introduction

The design of effective auditory displays requires an understanding of basic auditory capabilities, as well as an appreciation of the ways in which the perception of sounds can influence the cognitive and motor activities in which a person may be engaged. Although auditory capabilities are a major consideration in predicting the impact of auditory displays, the design of an effective display also requires an appreciation of response proclivities, that is, the specific effects that various sounds have on listeners, in terms of the responses that they normally elicit. This distinction between capabilities and proclivities is based strictly on the operations of measurement that are appropriate for determining the behavior that can be, or typically is, elicited by sounds, not on the basis of the origins of the two aspects of sense-based behavior (e.g., in learned vs. innate associations, or in central vs. peripheral mechanisms). Auditory capabilities include whether a sound can be heard (detected), what changes in it can be resolved, and whether it can be identified when presented as a sample from some specified catalog. The limits of auditory capability define the properties of the auditory system with reference to a specific sound, or class of sounds, in terms of sensitivity, acuity, and an as-yet-poorly-understood combination of limits on attention and memory. Proclivities reflect responses to sounds that generally cannot be scored as right or wrong. Examples include judgments of sound quality, of the value of a sound on one or more perceptual scales, or of the similarity of sounds to one another. (See Table 1 for additional examples of capabilities and proclivities and a summary of distinguishing characteristics.)

An appreciation of the distinction between capabilities and proclivities can be helpful in the design of auditory displays and in the evaluation of the potential for an auditory display to facilitate the appropriate responses. This paper deals primarily with some of the limits of auditory capabilities that have significance for the design of auditory displays. A few relevant proclivities are also considered in later sections in which more specific guidelines for the design of auditory displays are discussed.

	Capabilities	Proclivities
Examples	Sensitivity Spectral resolving power Temporal resolving power Auditory memory Max. information transmitted	Loudness Similarity of multidimensional sounds Emotional content/value "Meaning" of sounds
Criteria	"Correct" response known to investigator. Specific responses not relevant	No *a priori* definition of a correct response Specific responses convey essential information
Preferred Testing Method	Feedback Train to asymptotic performance Minimal Uncertainty testing (unless interested in limited learning opportunities, or in levels of stimulus uncertainty)	*No* feedback Limit training to that required to obtain reliable measures "Natural" levels of stimulus uncertainty

Table 1: A summary of the distinction between capabilities and response proclivities.

1.1 Limits of human auditory capabilities

Human listeners are capable of learning to detect remarkably small differences between complex sounds, but they may take very long to do so if confronted with a large catalog of such differences to be learned (as discussed below). The necessary months or years of training may often be deemed uneconomical in the extreme, particularly if some form of automatic (often computer-based) processing can do an equal or better job. However, because of the human's inherent abilities to generalize and to recognize commonalities among stimuli that might elude many automated systems, there may be instances in which the perceptual and decision-making skills of the human observer are worth honing to a fine edge.

To illustrate the capabilities of the human listener, here are some examples of trained skill in the discrimination among the members of high-information-content catalogs of sounds, as measured in a series of experiments (for additional details see Watson [30]; Watson and Foyle [31]; Watson, Foyle, and Kidd; Kidd and Watson [15]). The stimuli were tonal patterns, generally ten-tone sequences of 40-msec tones, ranging from 300 to 3000 Hz. Listeners in these experiments were trained to detect changes in frequency, intensity, or duration, or in the presence or absence of single tonal components. A trial usually consisted of a standard pattern, followed by two test patterns, one of which was identical to the standard, the other of which differed in the properties of a single tonal component. Subjects were trained until they approach asymptotic performance, often requiring extended training times.

In another version of this type of experiment, one of the tones in the standard pattern is replaced by a silent gap. One of the two test patterns is again identical to the standard, but the other includes a "target" tone instead of a gap. The subject's task is to identify the test pattern containing the target tone. When all of the nontarget, or context, tones are presented at 75 dB, SPL, listeners can learn to detect the target tone at levels as low as 20–25 dB. A major conclusion from these tonal pattern studies is that stimulus complexity, per se, does not have a significant degrading effect on listeners abilities to resolve the details of a waveform. Under optimal testing conditions listeners can learn to detect changes in the frequency, intensity, and duration of single 40-msec components of ten-tone patterns with an accuracy that approaches that achieved when

Uncertainty	Frequency	Duration	Intensity	Detection (dB, SPL)
High	2400 Hz	56 msec	9.9 dB	58 dB
Medium	49 Hz	27 msec	6.8 dB	46 dB
Low	16 Hz	6.7 msec	2.5 dB	25 dB

Table 2: Detection and discrimination thresholds ($d' = 1.0$) for a 554 Hz, 40-msec tone presented in a ten-tone pattern, under three levels of stimulus uncertainty (from Watson [30]). Non-target tones always at 75 dB, SPL.

the same tones are presented in isolation.

This remarkable pattern discrimination performance is, however, only achieved under the "optimal" testing conditions referred to above. Those conditions are that only one pattern is presented from trial to trial, for many hundreds of trials in a row, and the same tonal component is always designated as the target. This has been termed a "minimal-uncertainty psychophysical testing procedure." In other versions of this experiment the level of stimulus uncertainty is varied in several ways. In intermediate-uncertainty conditions the same pattern may be used on every trial, but the element subject to change (the target tone) may be varied. Still higher levels of uncertainty are accomplished by presenting a new tonal sequence on each trial. Table 2 illustrates average thresholds for detection and discrimination by highly trained listeners under various levels of stimulus uncertainty.

The data in Table 2 show that the effects of stimulus uncertainty on the resolution of individual components of complex patterns is very large compared to the corresponding effects for single tones presented in isolation. Various investigators have studied the changes in the detectability and discriminability of single tones when the tonal frequency is varied from trial to trial (see Watson, et al. for a summary of these experiments). In the single-tone case, the threshold for detection increases by 1.0–2.0 dB as a result of stimulus uncertainty, in contrast to the 33 dB shown in Table 2 for individual components of a tonal pattern. Increases in *discrimination* thresholds associated with stimulus uncertainty are also considerably larger for components of tonal patterns than for isolated tones.

A recent series of experiments has shed some light on the nature of the uncertainty limitations and on auditory processing in general. The basic high uncertainty frequency discrimination experiment was replicated for patterns with various numbers of components (from one to ten) and also for various durations of the total patterns (from 64 msec to 2.0 sec) and of the individual components (Watson, Foyle, and Kidd; Kidd and Watson [15]). It was found that the strongly degrading effects of stimulus uncertainty occur when the portion of a sound that is subject to change occupies less than 20–30% of its total duration. Moreover, despite the wide range of durations and of numbers of components, most of the variance in discrimination performance was accounted for by the proportion of the total duration (PTD) of the component subject to change. This relation between discrimination performance and proportional duration, termed the PTD rule, has also been observed with another class of stimuli by Coble and Robinson [4]. They investigated "frozen" noises, in which one temporal segment of a burst of noise is repeated, while the remainder is a new noise sample. In general these results suggest that when presented with a temporally discrete novel sound, a limited processing capacity (or limited attentional resource) is uniformly distributed over the total duration of the sound, regardless of the total duration.

Another determinant of auditory capability is the size and composition of the set of sounds of which the one to be identified is a member. The ability of human listeners to learn new languages, Morse Code, or the subtle differences among the sounds of human hearts, suggest a remarkable capacity to establish meaningful responses to large arrays, or "vocabularies," of auditory stimuli. Considerable research, however, has shown there to be serious practical limits to the size of signal arrays that operators may be expected to learn to use with realistic amounts of training. One of the best known commentaries on this matter is Miller's [21] summary of human subjects' abilities to categorize, or classify, both visual and auditory stimuli that vary in only one physical dimension, such as intensity or frequency. Miller's conclusion, since supported by many experimental studies, was that human listeners' judgements appear to be limited to the accurate use of no more than "seven, plus-or-minus two" response categories (i.e., three-plus bits of information). When stimuli differ in more than one dimension, this limit can be exceeded, yielding somewhat more information transmitted by the human listener, but often by no more than an additional bit or so (Pollack [24]; Pollack and Ficks [25]). These rather drastic limits on listeners' abilities to cope with large signal arrays, as demonstrated in early laboratory studies, have been shown by Patterson [22] to be consistent with performance in identifying the warning signals used on civil aircraft. He attempted to teach groups of naive listeners to identify a set of ten clearly distinguishable auditory alarms, from among those in current use. Listeners were able to quickly learn to identify subsets of six or seven of the signals, but their learning time was greatly extended, possibly beyond practical limits, when all ten signals were introduced. Similar results were reported by Leek and Watson [17], who trained listeners to identify 24 tonal sequences, representing all of the possible permutations of four, three-tone "syllables." In a preliminary training phase of that experiment, four three-tone stimuli were identified with nearly perfect accuracy, and short response latencies, after less than one hour of training. However, learning to identify two-, three-, and four-element concatenations of the basic three-tone elements was extremely difficult. After 30–40 hours of training some listeners reached 90% accuracy for the set of 24, four-element sequences, but none could achieve the high accuracy and short response latencies expected for an array of auditory warnings. It was also found that, although all of the subjects had clinically normal hearing and were university graduates, there were very large individual differences among them in the levels of identification performance achieved after prolonged training.

The well-studied human abilities to learn new languages and to detect remarkably subtle changes in complex waveforms may seem at odds with these findings of very poor performance in learning to identify relatively small arrays of auditory signals. Table 3, from Watson, may shed some light on this problem. This table shows the amounts of training that have been required to approach asymptotic performance on various auditory tasks for simple and complex stimuli. These times range from one hour to many months, possibly extending to years. The organization of the table illustrates a simple generalization. The more information transmitted by the listener's response, the longer the time course of auditory perceptual learning. The columns of the table represent the three basic auditory tasks studied in research laboratories: detection, discrimination, and identification. The rows roughly distinguish between low- and high-information content stimuli, in most cases "simple" refers to single tones. The most rapid learning, as might be expected, is for the detection of single tones and the slowest is for the identification of complex sounds. Still the most well-documented study of the time course of human auditory perceptual learning is the study of Morse Code by Bryan and Harter [2] in 1899. Those pioneering investigators from Indiana University measured an almost linear increase in characters per minute that could be correctly identified, extending over a period of 48 weeks, with four to six hours of training per day. These results suggest that most modern studies of the ability to learn similarly difficult tasks, typically limited to training for one hour per day for a few weeks, have greatly underestimated the auditory capabilities of the human listener. But they also support Patterson's and others conclusions that with realistic training times, we should limit auditory arrays to rather small amounts of critical information.

	Task		
Stimuli	Detection	Discrimination	Identification
Simple	1.6 h (1) 1.0 h (2) 1 wk (3)	4 h (4) 4 h (5) 7 h (6)	24-28 wks (7) 20 h (8) 4 wks (9)
Complex	<14 h (10) <30 h (10)	6 h (11) >20 h (12)	>40 wks (13) >60 h (14) >36 h (15)

Table 3: Time required to approach asymptotic performance in the detection, discrimination and identification of simple and complex sounds. References: (1) Zwislocki et al. [36]; (2) Gundy [8]; (3) Watson, et al. [32]; (4) Campbell and Small [3]; (5) Leob and Holding [18]; (6) Watson and Kelly [33]; (7) Meyer [20]; (8) Tanner and Rivette [28]; (9) Hartman [9]; (10) Watson and Kelly [34]; (11) Warren [29]; (12) Leek and Watson [16]; (13) Bryan and Harter [2]; (14) Leek and Watson [17]; (15) Espinoza-Varas and Watson 1986.

1.2 Selection or Design of Auditory Displays

A consideration of the results discussed above will often be a necessary part of the design of an effective auditory display. However, several other factors have been identified, not all of which are based on the limits of auditory capabilities. Many of these factors have been identified in reviews of the literature on the design of auditory signal arrays published by Deatherage [5], Sorkin, Boff and Lincoln [1], and Patterson [22, 23].

The first consideration in the design of auditory signal arrays is, of course, that they will be audible and identifiable in the context in which they are to be used. Audibility is no longer a difficult problem, since general theories of masking have been advanced to the point that it is possible, in most detection tasks, to predict performance by simply comparing the power spectrum of the background noise to that of the intended signals. Detailed procedures for predicting the thresholds of complex signals in noise are provided by Patterson [22], employing filter shapes that closely approximate those of the human listener. It must be emphasized, however, that detectability does not imply identifiability. Signals are detectable when their most prominent spectral components exceed the threshold established by the environmental masking noise. For identification, not only must some portion of the signal be clearly heard, but all of the components necessary to its correct identification must be audible.

Once we have assured that all relevant portions of the display are audible, what are the desirable properties of the necessarily limited arrays that can be employed? Two simple general rules can be proposed. First, the members of the array should each be perceptually salient and distinct from the other members. Second, the auditory signals should not be presented in such a way that they interfere with the efforts of operators to carry out the responses that the signals are intended to elicit from them. "Salience" means that the signals will be readily noticed as a new sound, differing markedly from the ongoing acoustic background. As a general rule, temporal properties may be more valuable than spectral properties, although both can be of value in achieving this goal. (The importance of one spectral property was demonstrated by Watson et al. who demonstrated that high-frequency components of novel auditory sequences are resolved with greater accuracy than middle- or low-frequency components.) Thus a "wailing" siren (one with pitch fluctuations over time) is more attention demanding than one with fixed-frequency and is also less likely to be masked by fixed-frequency peaks in the spectrum of the ambient background. Sirens in general, however, have two properties that limit their value as alerting signals, particularly in the confined space of a cockpit or control room. One is that only a very small number of distinctly different siren-style sounds can be included in a signal array. The other is that ongoing siren-like sounds have too often been presented at levels that interfere with the performance of the desired responses to them. This occurs either because the intense ongoing warning elicits a "panic" response that precludes orderly, rational, adaptive behavior, or by making necessary communication between multiple operators virtually impossible. Patterson and Milroy from whose work most of the above comments derive, and Sorkin [26] advise limiting the level of warning signals to 16–22 dB above their (masked) detection thresholds. If signals in excess of 95–100 dB, SPL, are required to achieve these sensation levels (dB above threshold), it is probably necessary to shift to visual or vibrotactile warnings.

While there are few systematic studies of the relative effectiveness of various spectral and temporal signals, a great deal of research provides indirect support for the generalization that temporally coded signals (or temporally and spectrally coded signals) are preferable to spectrally coded ones. The auditory nervous system, like the other senses, shows greater sensitivity to dynamically varying stimuli than to static ones. The information content of human speech is heavily concentrated in the temporal properties of the consonants. Many musical instruments are more accurately identified by their sounds when listeners are presented with only the attack and release portions of the sounds than when only the "steady-state" portions are presented. The recently adopted international standard building-evacuation signal, consisting of three 0.5-sec pulses of virtually any audible signal, separated by 0.5-sec silent intervals, illustrates one standards committee's support of this principle.

Temporal factors can also affect listeners' abilities to resolve particular components or component relations within complex auditory displays. Jones, Kidd, and Wetzel [11] have shown that temporal structure can facilitate temporal-order discrimination by contributing to the perceptual segregation of subsets of tones in auditory sequences. More recently, Kidd [12, 13] has shown that resolving power is considerably degraded for tones that are temporally displaced with respect to an established rhythmic context. These results suggest that an analysis of the temporal structure of an auditory display and the context in which it is presented should be included among the design considerations.

1.3 Sound Quality

Another factor that can influence the effectiveness of an auditory display has recently been termed "sound quality." In industry, there has been a growing interest in designing the sounds produced by various sound-emitting products (e.g., automobiles, sewing machines, vacuum cleaners) in an attempt to make products more appealing to consumers (e.g., Lyon [19]). While the sounds of interest typically are not part of a formal auditory display (i.e., the auditory information is often not presented explicitly to assist in the operation or monitoring of the device), sound quality can influence an operator's performance even when the sounds are merely incidental. For obvious reasons, a major concern has been with removing those properties of sounds that are perceived as annoying. (Traditionally this was addressed simply by reducing the level of the offending sound.) However, there is increasing interest in tailoring sounds to create an impression of more specific desirable properties of products. For example, all car sounds should convey high quality, but a quality sports car should sound "sportier" than a luxury car.

Sound quality is typically assessed via rating-scale judgments made by juries of listeners. This is clearly a proclivity measure (see earlier discussion of capabilities and proclivities) in that listeners' responses cannot be scored as correct or incorrect. However, such judgments of quality may be closely related to listeners' ability to identify the types of objects (or materials) and events that are generating the sounds. We need to know more about listeners' abilities to identify properties of objects and events via auditory information (see Gaver [6, 7]) if a general theory of sound quality is to be realized. An understanding of the acoustic parameters associated with listeners' identification of specific sound-producing materials and events would definitely help design displays that have desirable sound qualities. Research on sound quality and ecological acoustics is now in its infancy, but both areas of research promise to provide some useful principles for the development of effective auditory displays.

1.4 Individual Differences in Auditory Capabilities

A final factor that can have a significant impact on the effectiveness of auditory displays is that of individual differences. Individual differences from the population mean (for young adults with normal hearing) in detection, discrimination, and identification performance with complex sounds are considerably larger than those for simpler sounds. Watson and his colleagues (Watson et al. [35]) have developed a test battery, termed the Test of Basic Auditory Capabilities (TBAC), that has been used to evaluate individual differences for a variety of auditory capabilities. The TBAC includes eight subtests: three with single tones (frequency, intensity, and duration discrimination), three with complex patterns (rhythm, sequence, and tonal-pattern discrimination), and two with speech stimuli (syllable-sequence discrimination and nonsense-syllable identification). The considerable range of performance obtained on each subtest of the TBAC, for a population of 127 normal listeners, is shown in Table 4 (from Watson [30]). Thresholds for each of the measures for the worst ten percent of the listeners are three to five times larger than for the best ten percent (e.g., from 3 Hz to 19.5 Hz for simple frequency discrimination, from 27 msec to 98 msec for the duration of tones in the tonal ordering task, and from 85 msec to over 250 msec in the syllable sequence-order task). One surprising finding, in light of the large range in performance is that factor analyses of the data imply considerable common variance among the nonspeech tasks, but not between them and the speech tasks. This result, together with work by several other investigators, has convinced us that performance on very familiar sets of complex stimuli may not be predictable from performance on the discrimination of unfamiliar sounds. Many experiments suggest that central, or "cognitive" factors of learning, memory and attention may have to be considered to predict human operators' performance with candidate arrays of auditory signals, rather than relying on psychophysical measures of spectral and temporal acuity obtained with simple sounds (pure tones, noise bursts, etc.).

Individual differences in preferential allocation of auditory attention may be an especially important factor to consider in the design of auditory displays. For example, it is common for listeners to elect to attend to different aspects or properties of complex sounds, often to the exclusion of other properties. This was observed in experiments with multidimensional complex sounds (Kidd and Watson [14]), in which listeners were asked to categorize 100-msec sound pulses on the basis of three attributes. Each sound pulse consisted of five simultaneous sinusoids. The attributes were spectral shape, temporal envelope, and harmonicity of the generating sinusoids. Although all listeners could discriminate between the sounds quite well when the task required attention to only one attribute, when attention to all three attributes was required, most listeners were sensitive to changes in only one or two of the three attributes. Roughly equal numbers of listeners displayed preferential processing of each of the three attributes. For 12 of the 27 listeners tested, the change in a single dimension accounted for two to four times as much of the variance in their categorization responses as was accounted for by either of the other two dimensions. Examples such as this serve as a reminder that listeners' capabilities as tested in simple tasks are sometimes poor predictors of performance in more complex tasks in which differences in

Test	Percentile				
	10	25	50	75	90
Pitch [Δf (Hz)]	19.532	11.629	6.447	3.747	3.010
Intensity [Δf (dB)]	3.154	2.123	1.223	0.560	<0.500
Duration [Δf (Hz)]	64.677	46.279	30.442	23.369	19.166
Rhythm [ΔT (msec)]	20.283	13.671	9.727	6.986	5.661
Embedded Tone [ΔT (msec)]	77.101	57.847	39.807	32.989	22.310
Temporal Order (Tones) [ΔT (msec)]	98.489	62.442	51.404	35.212	27.761
Temporal Order (Syllable) [ΔT (msec)] /FA/TA/KA/PA/	>250.000	217.318	163.544	125.010	85.949
Syllable Identification [P(c)] (NST)	0.519	0.556	0.611	0.667	0.722

Table 4: Population performance for 127 normal-hearing college students on the Test of Basic Auditory Capabilities (TBAC). Performance measures represent thresholds fitted to psychometric functions for subjects at the 10th, 25th, 75th, and 90th percentiles of this population (Watson et al. [35]).

attentional strategies and other cognitive factors can strongly influence performance.

1.5 Special Populations of Listeners

It has long been thought, particularly by some musicians, that "the musical ear" is a more accurate receiver than the auditory apparatus of lay persons. Under controlled testing conditions, however, it is difficult to find evidence favoring the existence of such an "auditory elite." In a study of tonal pattern discrimination by musicians versus nonmusicians (Spiegel and Watson [27]) we first tested a sample of 217 college students whose musical backgrounds varied from zero to fifteen years of formal musical training. We determined the strength of the association between their abilities to discriminate subtle spectral changes in word-length ten-tone patterns and the number of years of their musical training. We also obtained data on the musicianship of the immediate families of these subjects, the number of hours per day the subjects practiced, and many other statistics that might reflect their overall musical involvement (including, for example, whether they currently belong to a musician's union). No statistically significant relations were found between these students' musical experience or musical preferences and their ability to hear out details of the tonal sequences, although broad ranges of both psychophysical performance and musicianship were represented in the data. In a follow-up study we had the opportunity to test a much more accomplished group of musicians. The same tests, plus some additional measures of pitch discrimination, were given to 30 members of the St. Louis Symphony Orchestra. These highly skilled musicians had more accurate discrimination thresholds, on the average, than a group of similar-age nonmusicians. However the *modal* performance of the musicians was approximately the same as for the nonmusicians. It appears that there are many nonmusicians whose discrimination abilities are as good as those of the best musicians, but there are *no* musicians with as bad abilities as those of the worst nonmusicians. Not terribly surprising, if you have extremely poor pitch perception you probably do not become a musician. But the converse does not seem to be true, those who do become musicians do not have auditory skills that are particularly unusual in the larger population. In addition to comparing the musicians to the nonmusicians on the tonal-pattern discrimination task, for which neither group had been explicitly trained, we compared them to another group who had been highly trained on those stimuli. These were our laboratory test subjects who had heard other tonal patterns several thousand times. The lab-trained subjects outperformed all of the musicians by a considerable amount. These results led us to test another group of "expert listeners," members of the Cardiology Department of the Washington University Medical School. These teaching physicians, residents, and nurses were considered by their colleagues to have great skill at hearing out subtle details of heart sounds. As with the musicians, the clinicians' abilities to detect changes in complex sounds with which they were unfamiliar were no better than those of typical listeners. These data are consistent with the general conclusion that the range of individual differences in "raw" auditory abilities is small relative to the range of performance on discrimination tasks due to differences in listeners' familiarity with the test sounds.

1.6 Some Recommendations

Recent research in psychoacoustics, briefly surveyed in the preceding discussion, provides support for the following rules for the selection or design of auditory displays.

1. Auditory capabilities determined under minimal uncertainty are both valid descriptions and misleading guides.
2. Auditory capabilities determined under high levels of stimulus uncertainty or under "ecologically valid" conditions can be both invalid descriptions and useful guides.
3. Performance on auditory identification tasks can be greatly improved through intense training, but pilots, cardiologists, and nuclear power station operators aren't likely to devote the required hours in learning an arbitrary auditory catalog of more than 7 or 8 discriminable sounds.
4. One way to convey more information is to use the auditory signal only to indicate (a) that a message has arrived and (b) the priority of that message. The actual message then can be conveyed by voice or by alphanumeric display.
5. Establishing larger catalogs of auditory signals may be possible, but may benefit from: (a) exploiting pre-existing sound-event associations, (b) designing sounds with maximal pairwise discriminability, based on psychoacoustic principles, (c) establishing a grammar, or other form of sound organization.

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