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EXTRACTING MEANING FROM SOUND: NOMIC MAPPINGS, EVERYDAY LISTENING, AND PERCEIVING OBJECT SIZE FROM FREQUENCY

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In developing a theoretical framework for the field of ecological acoustics, Gaver (1993b) distinguished between the experience of musical listening (perceiving sounds) and everyday listening (perceiving sources of sounds). Within the everyday listening experience, Gaver (1993a) proposed that the frequency of an object results from, and therefore specifies, the size of that object. The relation in which frequency and object size stand to one another is an example of a nomic mapping. A symbolic mapping involves the pairing of unrelated dimensions and, relative to a nomic mapping, requires an additional step in recognition and learning. Using a perceptual identification task, an experiment investigated the hypothesis that nomic mappings are identified more easily than symbolic mappings. It was predicted that the advantage manifests only during the everyday listening experience, and that the initially superior recognition of nomic mappings is equaled by symbolic mappings after extended exposure. The results provided support for the hypotheses. Theoretical implications of the differential recognition of nomic and symbolic mappings are discussed, together with practical applications of nomic relations.

While speech and music perception have received considerable attention in experimental psychology (Deutsch, 1999; Jusczyk, 1997), relatively little is known about the way in which humans perceive other environmental sounds. Recent research in ecological acoustics has focused on the way in which a sound may contain meaningful information for the listener (e.g., Ballas, 1993; Ballas & Howard, 1987; Carello, Anderson, & Kunkler-Peck, 1998; Gaver, 1986, 1989, 1993a, 1993b;

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Heine & Guski, 1991; Jenison, 1997; Rosenblum, Wuestefeld, & Anderson, 1996; Stoffregen & Pittenger, 1995; Walker & Ehrenstein, 2000; Warren & Verbrugge, 1984). Gaver (1986) proposed that acoustic properties of sound convey information that enables identification of an event. Sounds and events that express consistent information regarding the source are termed nomic mappings, whereas symbolic mappings involve unrelated or arbitrary sound-event pairs. Gaver predicted that the redundancy of information expressed in nomic mappings results in efficient and rapid recognition.

Surprisingly, few of today's 'informative' sounds build on the inherent meaning in nomic mappings. The ring of a telephone, the buzz of an alarm clock, and the wail of an ambulance siren have been designed to gain attention, but may require an additional cognitive step to extract meaning from sound. Although they are ultimately effective, symbolic mappings of this kind are likely to require an extended period of learning. This issue has important implications for the design of auditory icons—environmental sounds used to communicate information (Edworthy & Stanton, 1995; Gaver, 1989; Mynatt, 1997). Accordingly, the aim of the present study was to investigate the relative ease of recognizing or, if necessary, learning nomic and symbolic mappings.

Learning Sound-Event Relations

In categorizing various sound-event relations, Gaver (1986) refers to Gibson's notion of direct perception and adopts an ecological approach (Gibson, 1979). According to the direct perception view, sound contains invariant properties that indicate the physical characteristics of environmental objects and their interactions (Michaels & Carello, 1981). Within Gaver's framework, the structure of a sound does not specify one certain source, but rather constrains the range of events that could have produced the sound. As a result, the association between a sound and a specific event has to be learned. The association of a signal (sound) to a referent (event) can be conceptualized as a mapping (Familant & Detweiler, 1993). A *nomic* mapping involves the correlation of a sound with an event that is physically capable of producing the sound (Gaver, 1986). For example, the use of the sound of a burning fire to signal the presence of a fire is a nomic mapping as the signal and referent express the same event. By contrast, *symbolic* mappings are combinations devoid of causal association and rely on social convention for meaning (Gaver, 1986). By this definition, a fire alarm may be used to signal the event of fire.

Familant and Detweiler (1993) propose that both nomic and symbolic mappings contain a signal and an associated referent. Importantly, this conceptualization of nomic mappings is not dependent on the notion of direct perception. Within the direct perception framework the signal *is* the referent. However, nomic mappings may involve *mediated* perception: A sound that contains the same information as the event is used to stand for the event. From this perspective, nomic mappings differ from symbolic mappings only in the *degree* to which the characteristics of the sign correspond with that of the referent. However, in some circumstances nomic mappings implicate direct perception in the identification of characteristics of the sound-producing event.

Nomic mappings involve congruence between acoustic information and a physically related occurrence—the signal and referent feature sets are identical (Familant & Detweiler, 1993). Experimental research has shown that even young children find it relatively easy to match sounds to an appropriate event in just one trial (Jacko & Rosenthal, 1997). By contrast, the acoustic properties of the sound in a symbolic mapping bear no resemblance to the event it signals—such an association must be learned through contiguous exposure. Consequently, Gaver (1986) provided the, as yet untested, hypothesis that nomic mappings are more easily learned than symbolic mappings. In the present study, the early stages of exposure will be scrutinized for evidence of faster recognition of nomic mappings.

Identifying Nomic and Symbolic Mappings

One challenge for the field of ecological acoustics is to develop a taxonomy of nomic mappings. The majority of studies have examined the perception of complex sounds in their natural environment (e.g., Vicente & Burns, 1996) and results indicate that both adults (Lass, Eastham, Parrish, Scherbick, & Ralph, 1982; Keller & Stevens, 2004) and children (Jacko, 1996) can identify the source of environmental sounds. One assumption underlying these studies is that the sound produced during each event is unique and must be learned by the individual, implying that a taxonomy of nomic mappings requires as many sounds as there are objects and events. Although such empirical endeavors contribute to understanding organism-environment interaction, they fail to identify invariant mappings between specific acoustic features and the corresponding properties of the sound source (Aslin & Smith, 1988).

An exception is the psychophysical investigation reported by Warren and Verbrugge (1984) demonstrating that the differentiation of breaking and bouncing glass objects is dependent on the temporal properties of sound. Warren and Verbrugge concluded that sound-source perception might be reduced to invariant temporal and spectral components. Specific acoustic features were thus considered as indicators of particular properties of the sounding object. Gaver (1993b) also adopted a reductive approach, speculating that causal relations exist between certain acoustic properties and source parameters, and that such mappings are invariant across sound-producing objects and events. Specifically, Gaver (1993a) proposed that frequency is an invariant indicator of size (when other source attributes remain constant). Larger objects vibrate with larger oscillations and consequently produce lower frequencies than those of smaller objects.

The significance of a reductive, psychophysical approach is that a finite set of invariant relations can be used to produce an infinite number of nomic mappings. Gaver (1993a) advanced this notion by developing a number of algorithms for synthesizing complex sounds. One algorithm, when entered into a sound synthesis program, replicates the sound of a bar being struck with a mallet. The equation is:

$$G(t) = \sum_n \Phi_n e^{-\delta_n t} \cos\omega_n t$$

where $G(t)$ describes the waveform over time, Φ_n is the initial amplitude, δ_n the damping constant, and ω_n the frequency of partial n. This algorithm produces a general impact sound, with the shape of the sounding object expressed through the pattern of partial frequencies. The sound of a struck bar is then produced by specifying this pattern, such that:

$$\omega_n = (2n + 1)^2/9.$$

By changing specified parameters within the second equation it is possible to alter the perceived properties of the bar. For example, changing the value of the partial frequencies alters the perceived length of the bar, whereas changing the damping constant results in a perceived change of material. Consequently, a large number of objects and interactions can be synthesized by altering certain parameters of a single algorithm. Synthesis of the sound provides greater experimental control than that achieved by recording an actual acoustic event; it enables production of a novel sound that minimizes the effect of prior experience and learning, and allows precise manipulation of parameters. According to Gaver (1993a), a sound's lowest frequency component can reflect bar length, whereas either loudness, proposed to indicate force and/or proximity, or damping, proposed to indicate the material of a bar, could be used in symbolic relations to bar length.

Two experiments were conducted prior to the present study to investigate the validity of frequency-size as a nomic mapping and damping-size as a symbolic mapping. The two experiments were based on the speeded classification task of the Garner interference paradigm (Garner & Felfoldy, 1970). In the Garner paradigm, two dimensions are paired, with attributes on the second dimension either varied orthogonally or held constant (Melara & Marks, 1990). If participants classify the first dimension more slowly when the irrelevant dimension is varied then it can be assumed that the two dimensions interact in perception (Melara, 1989). The purpose of this procedure is to identify *integral dimensions* that combine to produce a unitary perception. The Garner procedure is valuable here as a means to identify invariant relations. According to Gaver's (1993a) predictions, the dimensions of frequency and length may be expected to interact as they provide redundant information; if one dimension conveys the same information as another then they may be considered perceptually integral (Melara & Marks, 1990). Nomic mappings were conceptualized as the association of two perceptually integral dimensions (as signal and referent depict the same event). Symbolic relations should not produce Garner interference as the two dimensions are perceptually separable.

There were four conditions in each experiment: In the baseline condition, the sound was held constant across all trials; in the random condition, sounds varied randomly; in the congruent condition a long bar was paired with low frequency or low damping constants and a short bar with high frequency or high damping constants; in the incongruent condition these combinations were reversed such that a long bar was paired with high frequency or high damping constants. At the same time as the sound played, participants were presented with a drawing of a solid long or short horizontal bar. In line with Garner paradigm procedures, participants were told to ignore the sounds and classify each bar as either long or short as quickly as possible. Mean reaction times for correct classifications of congruent, incongruent, and random pairings showed a trend for frequency and bar length to be perceptually integral or, in our terms, related (congruent mean = 347.49 ms, *SD* = 60.58; incongruent mean = 360.84 ms, *SD* = 40.31; random mean = 433.36 ms, *SD* = 36.66) and confirmed damping and bar length as a symbolic mapping (congruent mean = 344.37 ms, *SD* = 74.15; incongruent mean = 353.44 ms, *SD* = 59.81; random mean = 398.93 ms, *SD* = 59.51). That is, there was a perceived and consistent interaction between frequency and size but not damping and size.

Damping has no natural relation to size and the Garner interference paradigm demonstrates a lack of interaction or correlation between damping and size. Although the mapping was symbolic and arbitrary there can still be a systematic relation between signal and referent. For example, written language is both symbolic and systematic. Therefore the damping scale values increased systematically in keeping with increases in frequency values. However, in the case of damping, there should be no natural or direct relation to changing values of the size dimension.

Everyday versus Musical Listening

Importantly, a listener does not always pick up the invariant information conveyed by frequency and other acoustic features. Gaver (1993b) distinguished between two types of auditory perception that reflect the attentional focus of an individual. *Musical listening* is the experience of perceiving properties of the proximal stimulus as it reaches the ear. Sounds are perceived in terms of pitch, loudness, timbre, and other features typically analyzed by psychologists and psychophysicists (e.g., Rasch & Plomp, 1999). Alternatively, listeners can focus on the distal stimulus. Gaver (1993b) termed perception of the distal stimulus or sound source as *everyday listening* wherein perception of the event is made possible by perceiving invariant relationships as described by physical law. For example, the action of plucking a metal string suspended over a resonant cavity produces a specific pattern of air disturbances that can be produced only by a constrained number of objects and events. An individual engaged in everyday listening in this example perceives the pluck of a guitar string.

The research emphasis on musical, at the expense of everyday, listening is most likely a product of the assumption that auditory stimulation requires *processing* before it becomes informative. However, proponents of ecological acoustics counter this assumption, arguing that the structure of sound can hold meaning for the listener. The present study investigates experimentally Gaver's conception of everyday listening (perceiving the source of a sound) and musical listening (perceiving a sound), with the prediction that information regarding the sound source is accessible only during the everyday listening experience. This hypothesis was tested here by manipulating instructions to encourage either everyday or musical listening, a technique that has been shown previously to influence the expectations and performance of listeners (Ballas & Howard, 1987). Certain tasks may demand a particular listening mode. For example, discriminating between different melodies (e.g., Dowling, 1986) versus identifying the timbre of a voice or instrument (e.g., Rasch & Plomp, 1999). In the present controlled experiment, stimuli did not demand one or other mode and instructions were used to focus participants' attention on the sound or its source. As recognition of nomic mappings is evident only during everyday listening, the hypothesized perceptual advantage of nomic over symbolic mappings will not be evident during musical listening. Long-term recognition of both kinds of mapping will be examined by comparing accuracy recorded in immediate and delayed tests.

Aim, Design, and Hypothesis

The aim of the experiment was to examine the relative ease of perceiving nomic and learning symbolic mappings. The experiment employed a 2x(2x2) factorial design: the two mapping levels of nomic and symbolic, an immediate and delayed test phase, and the between-subjects factor of everyday versus musical listening. The dependent variable was the percentage of correct responses, a measure widely considered to be a valid indicator of recognition and learning in humans (Brand & Jolles, 1985; Greene, 1988; Savage & Gouvier, 1992). Recognition of nomic and symbolic mappings was tested using a variation of a paired-associate task (Leiser, Avons, & Carr, 1989). In this paradigm, participants are presented with associations 'online' and, if necessary, learn through the use of feedback. Participants were required to guess bar length at first exposure to test the claim that mapping structures are more readily available in the nomic condition. The main hypothesis under investigation was that nomic mappings are perceived more readily than symbolic mappings but that the advantage manifests only in the immediate phase of the everyday listening condition.

Method

Participants

Participants were 40 students from the University of Western Sydney. All participants had self-reported normal hearing and, for control purposes, no formal training in music.

Materials

Auditory stimuli. For the nomic condition involving the frequency dimension, a scale consisting of 10 sounds was constructed (see Appendix). Each had a damping constant of .01 and a duration of 300 ms. Using a wooden xylophone as a guide, an estimation was made of the bar lengths (measured in millimetres) necessary to produce these frequencies, when both bar width and thickness were held constant. Another 10 sounds were produced for the symbolic category of damping (see Appendix). By symbolic, we mean that there was no natural or logical relationship between damping and bar length. However, the scales shown in Table 1 indicate that the mapping of values in both nomic and symbolic relations was systematic and, for control purposes, use of a heuristic was possible in either condition. Frequency was held constant at 457 Hz, and duration was set at 300 ms, the natural length of the most damped sound. A pilot test with 6 adult participants showed that all sounds were distinguishable from one another.

The frequency scale was then matched with the measurements of bar length in units such that the nomic relationships were maintained. The symbolic mapping sounds were also organized into a scale, such that damping constants were, like the nomic mapping, negatively correlated with the associated referent measurements. This ensured that superior identification could not be attributed to the application of some heuristic in only the nomic, but not the symbolic, condition (e.g., as pitch goes down, size goes up). Two different lists were constructed to control for the assignment of referents. Participants were presented with either List 1 or List 2, with list counterbalanced across conditions. Signal-to-referent mappings for each list are presented in Table 1. Nomic signals refer to frequency in Hz, symbolic signals refer to damping rate, and the referent is length in mm.

Table 1

Signal to Referent Mappings for List 1 and List 2

List 1	Referent	List 2
Nomic condition		Symbolic condition
200 Hz	363	.001
288 Hz	327	.0026
415 Hz	290	.0067
598 Hz	254	.0171
862 Hz	216	.0438
Symbolic condition		Nomic condition
.0016	348	240 Hz
.0042	306	346 Hz
.0107	274	498 Hz
.0274	233	718 Hz
.0701	197	1034 Hz

Visual stimuli. Prior to hearing the struck bar stimulus, participants were presented with a green circle positioned in the center of the screen. This served as a focus for the mouse pointer and ensured that the pointer was equidistant from all numbers at the start of each trial. At the same time as the sound on each trial was presented, five numbers were displayed in a circular configuration surrounding the area previously occupied by the green circle. The positions of the numbers were changed in each block to eliminate the effect of spatial memory. Bar length was represented in numerical terms, with a three-digit measurement in millimeters used to distinguish among the different lengths. Numbers of this type were used so that they were equal in terms of their familiarity, phonology, imagery, and numerical complexity.

It could be argued that the use of numbers to represent bar length is problematic in that they invoke a symbolic mapping. This issue highlights the complexity of measuring and quantifying behavioral responses to nomic relations. The use of a visual or iconic figure is no solution as the figure simply represents or stands for a particular object or event, and the just noticeable difference for visual lengths is also implicated. Numerals were chosen here for three reasons. First, the notion that numbers stand for or are symbolic of real physical states of the world assumes a representationist view of number and measurement (for review and critique, see Michell, 1986, 1990, 1999). An empirical realist conception of number and measurement, by contrast, considers measurements of quantitative variables as real entities conveying information directly about states of the world (Michell, 1990). For example, the description of tone frequency using quantities of cycles per second depicts a physical property of sound. Numbers indicating length are also real entities about spatial extent. We contend that length reported in numerical terms expresses the physical state of affairs. Second, the numerical values chosen were scaled versions of actual bar lengths that, when struck, would produce the particular frequencies. Third, Pansky and Algom (1999) used the Garner interference paradigm and demonstrated that numerical magnitude and physical size are perceptually integral.

Apparatus. The experiment was designed and conducted using *Powerlaboratory* (Chute & Westall, 1996) and was run on one of two Apple Macintosh computers; a Power Macintosh 7300/200 and a Power Macintosh G3. Auditory stimuli were synthesized using Csound. Participants in the everyday listening condition were given a 400-millimeter ruler to aid their conceptualization of the measurements. Two sets of stereo headphones were randomized in use (*Sennheiser HD 450 II*, and *AKG K270*).

Procedure

Participants were asked to position the computer mouse on their favored side of the keyboard and were fitted with headphones. On-screen instructions varied according to the listening condition. Participants assigned to the everyday listening condition were told that they would be presented with the sound of a struck pipe, and that this sound would be paired with the length of the pipe in millimeters.[1] Those in the musical

[1]The sound source was relabeled a pipe based on feedback from a seminar group.

listening condition were told that they would hear a sound and that it would be associated with a label. The task required participants to use the mouse to select the appropriate label after hearing a sound. Participants were given a brief practice phase to familiarize themselves with the procedure. After making each selection, feedback ("correct" or "incorrect") was given, followed by the correct value. Each of the five sounds was presented twice in random order within each block, and each mapping condition consisted of five blocks. The order of mapping condition was counterbalanced across groups. Evidence of retention and the effects of prior learning were assessed by repeating the test 1 week later (Barnard, Breeding, & Cross, 1984). The duration of each session was 30 minutes.

Results

Four orthogonal planned comparisons were performed to test the experimental hypotheses (Howell, 1997). Alpha was set at .046 to adjust for familywise error (Shavelson, 1988). The experimental hypothesis focused on the differences in the percentage of correctly mapped items between the nomic and symbolic conditions during the immediate and delayed test phase, within both the everyday and musical listening groups. Checking the assumptions for the dependent samples t test revealed that the range of scores for both the delayed-nomic condition of the everyday group and the immediate-nomic condition of the musical group was not normally distributed. However, as the sample size was reasonable and there were no univariate outliers, parametric procedures were used (Tabachnick & Fidell, 1996). The accuracy scores are shown in Figures 1 and 2.

Testing whether nomic mappings are recognized more easily than symbolic mappings in the everyday listening-immediate test phase, the mean percentage of correct responses for the nomic condition (M = 65.70%, SD = 9.83%) was found to be significantly greater than the symbolic condition mean (M = 55.80%, SD = 13.50%), $t(19) = 3.21$, p = .005. Regarding the hypothesis that the difference in recognition of nomic and symbolic mappings would not be maintained during the everyday listening-delayed test phase, the related comparison shows no difference between the nomic (M = 69.60%, SD = 8.79%) and symbolic scores (M = 70.50%, SD = 12.91%), $t(19) = .32$, $p = .75$. As hypothesized, the difference between the nomic (M = 62.80%, SD = 13.79%) and symbolic (M = 58.60%, SD = 16.29%) means in the musical listening-immediate condition was not significant, $t(19) = 1.13$, $p = .27$, as was the difference between the nomic (M = 67.80%, SD = 16.58%) and symbolic (M = 70.10%, SD = 12.03%) scores in the musical listening-delayed phase, $t(19) = .74$, $p = .47$.

Considering the large difference between the nomic and symbolic means in the everyday listening-immediate test phase on the first block (see Figure 1), it was possible that this difference alone may have produced the significant difference between groups. Three post-hoc comparisons were performed to determine whether the statistical support

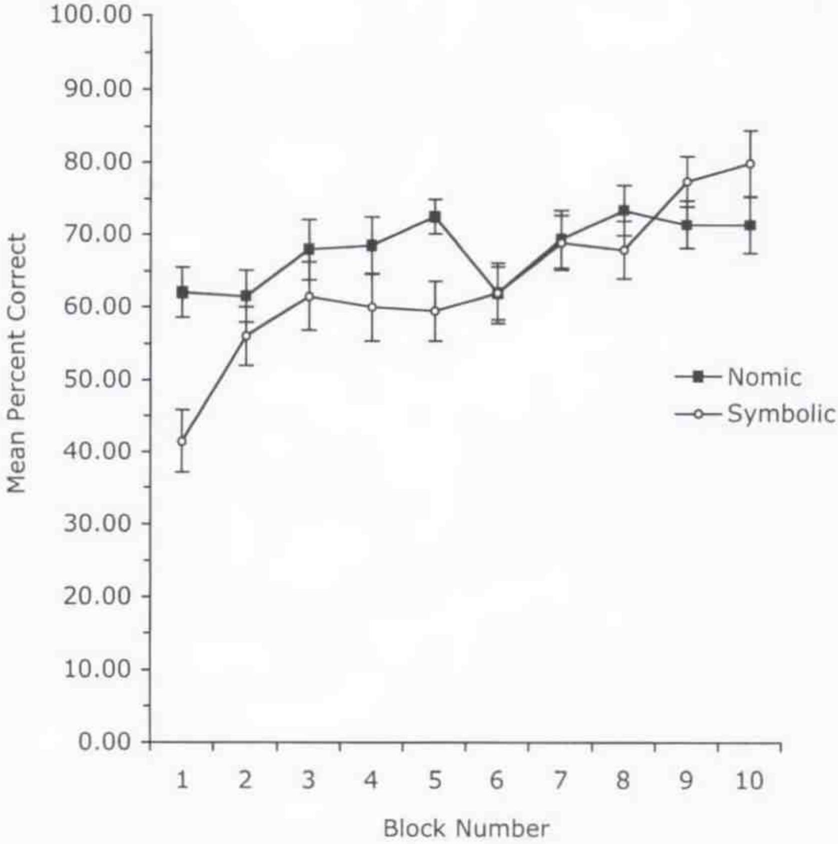

Figure 1. Mean percentage of correct responses for nomic and symbolic mappings in the everyday listening condition. Blocks 1 to 5 refer to the immediate testing condition and Blocks 6 to 10 refer to the delayed testing condition. Standard error of the mean is shown.

for the hypothesis was determined solely by responses on the first block. The assumption of normality was violated in Blocks 3 and 5 of the nomic condition, but the sample size and lack of outliers once again justified cautious use of parametric statistics (Tabachnick & Fidell, 1996). Alpha was adjusted for familywise error using a Bonferroni adjustment (Tabachnick & Fidell, 1996). This more stringent alpha level of .017 was necessary because of the previous orthogonal planned contrasts (Tabachnick & Fidell, 1996).

Descriptive statistics for each block within the everyday listening-immediate test phase are presented in Table 2. First, a one-way within-subjects ANOVA was performed on both the nomic and symbolic Blocks 2, 3, 4, and 5 within the everyday listening-immediate test phase. The analysis revealed no significant difference between the mean scores across the eight blocks, $F(7, 133) = 2.09$, $p = .05$, $\eta^2 = .099$. Consequently,

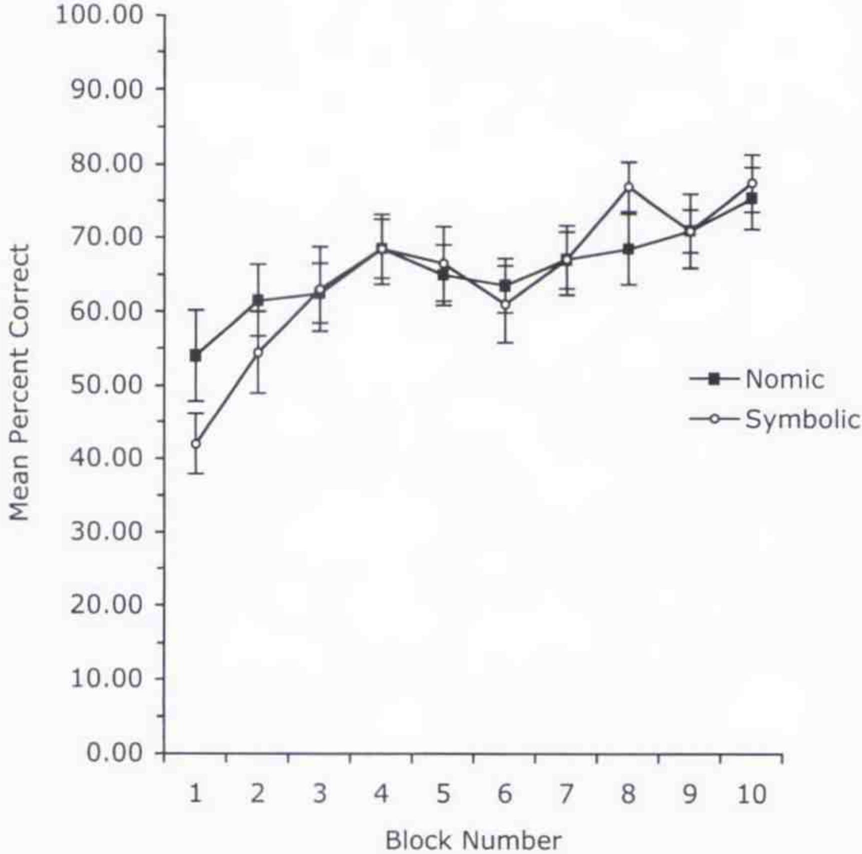

Figure 2. Mean percentage of correct responses for nomic and symbolic mappings in the musical listening condition. Blocks 1 to 5 refer to the immediate testing condition and Blocks 6 to 10 refer to the delayed testing condition. Standard error of the mean is shown.

the mean scores from these eight blocks were averaged ($M = 63.38\%$, $SD = 10.28\%$) for comparison during the following analyses. Second, the mean percentage of correct responses in the first block of the nomic condition within the everyday listening-immediate test phase was compared with the mean score of the eight blocks using a dependent samples *t* test, with no significant difference between the means, $t(19) = .74$, $p = .47$. Finally, a dependent samples *t* test found the mean for the first block of the symbolic condition within the everyday listening-immediate test phase to be significantly less than the mean of the eight blocks, $t(19) = 6.11$, $p < .001$.

Table 2

Mean Percentage of Correct Responses per Block for Each Mapping Condition in Immediate-Everyday Phase

Block Number	Nomic Mappings *M* (%)	Nomic Mappings *SD* (%)	Symbolic Mappings *M* (%)	Symbolic Mappings *SD* (%)
Block 1	60.00	18.06	40.50	18.77
Block 2	62.00	16.42	56.00	18.18
Block 3	68.50	18.72	63.50	20.84
Block 4	67.00	18.09	59.50	20.38
Block 5	71.00	11.65	59.50	18.49

Discussion

The results of this experiment support the hypotheses. Specifically, nomic mappings were recognized more readily than symbolic mappings, but the advantage was restricted to the initial phase of the everyday listening group. Performance in the everyday listening-delayed test phase shows no facilitation of nomic mappings and, at the end of the session, greatest accuracy was achieved in the symbolic mapping condition (Figure 1). Post-hoc analyses revealed that the difference in recognition of nomic and symbolic mappings was evident only during the first block of the everyday listening condition. This finding endorses the notion that mapping structures are more readily available in the nomic condition.

These experimental results are in keeping with the notion that certain acoustic dimensions convey information that constrains perceived source attributes, and that this information affords perception when paired with an event bearing similar characteristics. An ecological perspective provides an explanation of these findings. The nomic mapping of frequency size afforded useful information to participants about the length of the struck bar. The combination of the pitch of a sound with size is a nomic mapping because it conforms to unchanging physical laws or states of affairs and involves detection of a cross-modal structure. These conditions have accompanied humans throughout history and, through phylogeny, may provide the basis for direct event perception. However, the present experiment used adult participants highly familiar with relations between sounds and object size and, as a result, we cannot rule out the possibility that ease of perception of nomic mappings is the result of experience.

Implications for the Design of Auditory Icons

It appears that adults can determine the relative length of a struck bar from the acoustic quality of pitch. Importantly, this finding need not be restricted to impact sounds. Gaver (1993a, 1993b) suggests that more complex sound-producing events may be reducible to a *series* of impacts. For example, Gaver proposed that scraping involves multiple impacts as the moving object falls into depressions and hits raised ridges. As a result, the current research findings should generalize to a large number of events.

The perceptual advantages of nomic mappings are not necessarily confined to frequency. Damping indicates the material of a struck object, and amplitude, with its perceptual correlate of loudness, affords information about the proximity of an event and the force of the interaction (Gaver 1993a; Stevens & Keller, 2003). Warren and Verbrugge (1984) have illustrated the role of temporal properties during event perception. The challenge for ecological psychology is to investigate the perception of such relevant features and map these to the invariant information that they afford. The resulting taxonomy of mappings would provide a framework for understanding the meaning inherent in environmental sounds.

We have demonstrated that nomic mappings, as illustrated with frequency and object size, provide initial perceptual advantages over symbolic mappings. Although the advantages are realized only during the initial stages of exposure, readily perceived nomic mappings may minimize the need for training. If invariant relations are mapped together then the meaning of an auditory icon should be obvious and resistant to extinction (Keller & Stevens, 2004). However, the advantages of nomic mappings may extend beyond the realm of educational applications and form the basis for intuitive mappings to artificial events. As sounds in the modern world become more artificial, our auditory evolutionary heritage could be overlooked, leading to a sense of disassociation with our surroundings. This is particularly relevant regarding new technology, such as computer interface systems and complex operational environments. The major benefit of using auditory icons may be to reacquaint humans with a phylogenetically familiar acoustic environment.

Limitations and Future Directions

Criticisms of the current experiment could include their minimal application to perception in the real world: As a result of reductive psychophysical analysis the auditory stimuli were caricatures of everyday sounds. However, identification of the elements crucial for event perception prompted Gaver (1993a) to devise algorithms for synthesizing auditory stimuli. He reasoned that if an artificial sound produces accurate identification of the desired sound-producing event, then the essential spectral components have been included. The proposed one-to-one relationship between frequency and object size may be more complex in real world settings (Walker, Kramer, & Lane, 2000). Frequency is known to reflect the material and shape of an object, as well as its size (Gaver, 1993a). However, when the attributes of shape and material are held constant, there is probably a direct relationship between frequency and size (Gaver, 1993a). Despite the risk of corrupting the natural listening experience, a controlled laboratory experiment was considered most appropriate to investigate the current hypotheses.

Further empirical research is required in the field of ecological acoustics particularly in the context of everyday listening. Invariant acoustic properties need to be identified and mapped to source-related information. There are hypotheses proposed by Gaver (1993a) that remain to be investigated including the proposed relationship between acoustic damping and object material, and the relationship between loudness and object proximity / force of interaction. Research in this area will not only inform theories of auditory and event perception but will also guide the development of taxonomies of auditory icons, warning signals, and the use of meaningful sonification for communication in complex operational and human-machine environments.

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Appendix

Scales for Pitch and Damping

Two scales of 10 sounds were constructed to represent the acoustic dimensions of pitch and damping. In an attempt to make each step in the scales discriminable, the principles underlying the psychophysical laws of Weber and Fechner were used. *Weber's law* states that just noticeable differences (JNDs) are a constant proportion of the original stimulus (Cook, 1967). For example, the ability to discriminate a difference in pitch between two tones depends on the second being approximately 10% higher than the first (Geldard, 1962). *Fechner's law* is in accordance with this principle, asserting that each increase in stimulus intensity requires a larger increment for the perception of a JND (Cook, 1967).

Although Weber suggested a proportion of 1/10 for auditory stimuli, the pitch scale of the current study contained a more conservative ratio of 1/5. Beginning with the frequency of 200 Hz, 20% of the preceding frequency was added to each step of the scale. The subsequent scale consisted of the frequencies 200 Hz, 240 Hz, 288 Hz, 346 Hz, 415 Hz, 498 Hz, 598 Hz, 718 Hz, 862 Hz, and 1034 Hz. The dimension of damping required larger proportional increases to produce perceptible differences. After pilot testing the proportion of 50% for the damping scale, it was decided that an increment of 60% was necessary to produce reliable JNDs. The first sound was given the minimum damping constant suggested by Gaver (1993a) of .001. This value produced a sound with a metallic ring that decays slowly. The resultant scale contained the damping contants .001, .0016, .0026, .0042, .0067, .0107, .0171, .0274, .0438, and .0701.