Auditory Perception of Breaking and Bouncing Events: Psychophysics

William H. Warren, Jr.*
University of Connecticut

Robert R. Verbrugge
University of Connecticut and
Haskins Laboratories, New Haven, Connecticut

Research in auditory perception has tended to emphasize the detection and processing of sound elements with quasi-stable spectral structure, such as tones, formants, and bursts of noise. In the spectral domain, these elements are distinguished by frequency peak or range, bandwidth, and amplitude. In the temporal domain, acoustic analysis has often focused on the durations of sound elements, the intervals and phase relations between them, and the influence of these on pitch and loudness perception, temporal acuity, masking, and localization. The auditory system has often been approached as an analyzer of essentially time-constant functions of frequency, amplitude, and duration, on the assumption that complex auditory percepts are compositions over sound elements having those properties, with certain temporal interactions (Fletcher, 1934; Helmholtz, 1863/1954; Plomp, 1964; see Green, 1976).

The perceptual role of *time-varying* properties of sound has received less attention. Exceptions to this are found in research on amplitude and frequency modulation, including auditory phenomena such as beats, periodicity pitch, and frequency glides. In general, research on time-varying properties has been most common in the study of classes of natural events, such as human speech, music, and animal communication, where an analysis of sound into quasi-stable elements is often problematic. In the case of speech, for example, many phonemic contrasts can be defined by differences in the direction and rate of change of major speech resonances (see Liberman et al., 1956, 1967). Some research on the perception of music has also demonstrated the perceptual significance of time-varying properties. Identification of musical instruments, for example, is strongly influenced by the temporal structure of transients that accompany tone onsets (Luce & Clark, 1967; Saldanha & Corso, 1964). In particular, the relative onset timing and the rates of amplitude change of upper harmonics have been found to be critical properties of attack transients that permit distinctions among instrument families (Grey, 1977; Grey & Gordon, 1978). Animal vocalizations are similarly rich in time-varying properties (such as rhythmic pulsing, frequency modulation, and amplitude modulation), and many of these properties have been shown to be critical for distinguishing the species, sex, location, and motivational state of the producer (e.g. Brown et al., 1978; Konishi, 1978; Petersen et al., 1978).

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It is noteworthy that in each of these areas of research on natural events, the discovery or explanation of perceptually significant, time-varying acoustic properties has been motivated by an analysis of the time-varying behavior of the sound *source.* In the case of speech, for example, an analysis of speech production has been an integral part of the search for the acoustic basis for speech perception (e.g. Fant, 1960; Fowler, 1978; Fowler et al., 1980; Liberman et al., 1967; Verbrugge et al., 1985). It is also worth noting that researchers in these areas have often found it useful to characterize acoustic information in terms of *higher order structure* in sound—that is, in terms of functions over the variables of frequency, amplitude, and duration. Given the time-varying behavior of the sound sources involved, it is not surprising that many of these functions are time-dependent, defining rates of change and styles of change in lower order acoustic variables (for example, the direction, rate, and change in rate of formant frequency transitions). Finally, the example of systems capable of measuring higher order physical properties, such as area, without prior measurement of more elementary properties, such as length (Runeson, 1977), has encouraged some researchers to believe that, analogously, higher order acoustic structure may be directly detectable.

The role of time-varying properties in the perception of other familiar events in the human environment is largely unknown. Our goal in this article is to demonstrate that higher order temporal structure can be important for perceiving such events.

It is apparent from everyday experience that listeners can detect significant aspects of the environment by ear, from a knock at the door to the condition of an automobile engine and the gait of an approaching friend (see Jenkins, 1984). Such casual observations were corroborated in experiments by VanDerveer (1979a, 1979b). She presented 30 recorded items of natural sound in a free identification task and found that many events such as clapping, footsteps, jingling keys, and tearing paper were identified with greater than 95% accuracy. Subjects tended to respond by naming a mechanical event that produced the sound and reported their experiences in terms of sensory qualities only when source recognition was not possible. VanDerveer (1979a) also found that confusion errors in identification tasks and clustering in sorting tasks tended to show the grouping of events by common temporal patterns. For example, hammering was confused with walking, and the scratching of fingernails was confused with filing, but hammering and walking were not confused with the latter two events.

These results support the general claim that sound in isolation permits accurate identification of classes of sound-producing events when the temporal structure of the sound is specific to the mechanical activity of the source (Gibson, 1966; Schubert, 1974). If higher order information is found to be specific to events, whereas values of lower order variables per se are not, then it may be more fruitful to view the auditory system as being designed for the perception of source events via higher order acoustic functions, rather than for the detection quasi-stable sound elements. Schubert (1974) put this succinctly in his *source identification principle* for auditory perception: "Identification of sound sources, and the behavior of those sources, is the primary task of the [auditory] system" (p. 126).

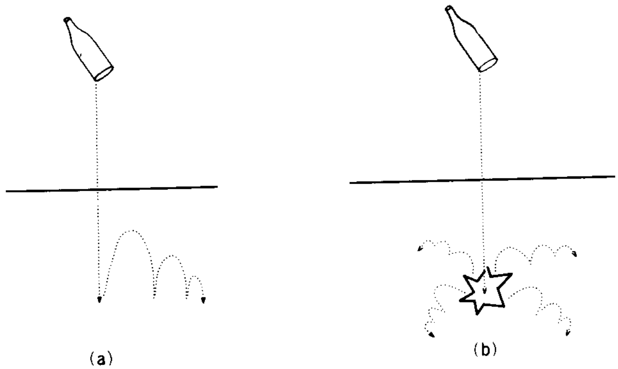

Figure 1 Caricatures of mechanical events: (a) bouncing; (b) breaking.

This general perspective on auditory perception may be called *ecological acoustics*, by analogy to the ecological optics advocated by Gibson (1961, 1966, 1979) as an approach to vision. The ecological approach combines a physical analysis of the source event, the identification of higher order acoustic properties specific to that event, and empirical tests of the listener's ability to detect such information, in an attempt to avoid the introduction of ad hoc processing principles to account for perception (Shaw et al., 1981). (*Ed. note*: the Natural Computation approach also includes these stages, but in addition requires a computationally based analysis of the inference process plus its instantiation.) In any natural event, identifiable objects may be viewed as constraining two characteristic properties of that event. The information of the event that specifies the kind of object and its properties under change is known as the *structural invariant* of an event; the information that reflects the style of change of the object's properties is known as the *transformational invariant.* These invariants may be described mathematically in terms of properties that remain constant and those that vary systematically under change (Mace, 1977; Mark et al., 1981; Pittenger & Shaw, 1975; Shaw et al., 1974; Warren & Shaw, 1984).

The present research explores the acoustic consequences of dropping a glass object and its subsequent bouncing or breaking. Bouncing and breaking are two distinct styles of change that may be applied to a variety of objects. By acoustic and perceptual studies of these events, we hope to identify the transformational invariants specific to the two styles of change and sufficient to convey them to a listener. (Structural invariants specifying individual properties of the objects such as size, shape, and material will not be discussed here.)

Consider first the mechanical action of a bottle bouncing on a hard surface (see Figure 1a). Each collision consists of an initial impact that briefly sets the bottle into vibration at a set of frequencies determined by its size, shape, and material composition. This is reflected in the acoustic signal as an initial burst of noise followed by spectral energy concentrated at a particular set of overtone frequencies. Over a series of bounces, the collisions between object and ground occur with declining impact force and decreasing ("damped") period, although some irregularities in the pattern may occur because of the asymmetry of the bottle. The spectral components are similar across bounces, with relative overtones varying slightly because of the varying orientations of the bottle at impact. (The spectrum within each pulse is quasi-stable and is conventionally described in terms of spectral peaks in a cross section of the signal.) These acoustic consequences may be described as *a single damped quasi-periodic pulse train* in which the pulses share a similar cross-sectional spectrum (Figure 2a). We suggest that this single pulse train constitutes a transformational invariant of temporal patterning for the bouncing style of change.

Turning to the mechanical action of breaking (Figure 1b), we see that a catastrophic rupture occurs upon impact. Assuming an idealized case, the resulting pieces then continue to bounce without further breakage, each with its own independent collision pattern. The acoustic consequences appear as an *initial rupture burst* dissolving into overlapping *multiple damped quasi-periodic pulse trains*, each train having a different cross-sectional spectrum and damping characteristic (Figure 2b). We propose that a compound signal, consisting of a noise burst followed by such multiple pulse trains, constitutes a transformational invariant for the breaking style of change.

Aside from these aspects of temporal patterning and initial noise, certain crude spectral differences between breaking and bouncing can be observed by comparing spectrograms of natural cases (Figure 2). First, the overtones of breaking events are distributed across a wider range of frequencies than are those of bouncing events. Second, the overtones of breaking are denser in the frequency domain. Both of these properties can be traced to the contrast between a single object in vibration and a number of disparate objects simultaneously in vibration.

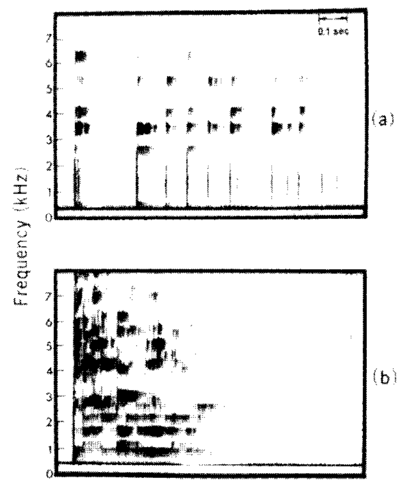

Figure 2 Spectrograms of natural tokens: (a) bouncing (BNC1); (b) breaking (BRK1).

The following experiments test the hypothesis that temporal patterning alone, without differences in quasi-stable spectral properties, provides effective information for listeners to categorize breaking and bouncing styles of change. (Spectral differences may provide important information about the nature and material of the objects involved.) By superimposing recordings of pulses from individual pieces of broken glass, artificial cases of breaking and bouncing can be constructed from a common set of pulses by varying the temporal correspondence among their collision patterns. In Experiment 1 we establish that listeners can categorize natural cases of breaking and bouncing with high accuracy. In Experiment 2, we examine performance with constructed cases that include an initial noise burst and compare it with the results for natural sound.

Experiment 1: Natural Tokens

The first experiment investigated whether natural sound provides sufficient acoustic information for listeners to categorize the events of breaking and bouncing.

Method

Subjects. Fifteen graduate and undergraduate students participated in the experiment for payment or course credit.

Materials. Natural recordings were made of three glass objects dropping onto a concrete floor covered by linoleum tile in a sound-attenuated room. The sound of each object was recorded with a Crown 800 tape deck when the object was dropped from a 1-ft (0.305 m) height (bouncing) and when it was dropped from a 2- to 5-ft (0.61-1.525 m) height (breaking). This procedure yielded three tokens of bouncing and three tokens of breaking. The objects used and the durations of the bouncing (BNC) and breaking (BRK) events are as follows: (a) 32-oz (0.946 l) jar; BNC1 = 1.600 ms, 22 collisions; BRK1 = 1,200 ms. (b) 64-oz (1.892 l) bottle: BNC2 = 1,600 ms, 15 collisions; BRK2 = 550 ms. (c) 1-liter bottle: BNC3 = 1,300 ms, 17 collisions; BRK3 = 700 ms. The recordings were digitized at a 20-kHz sampling rate using the Pulse Code Modulation (PCM) system at Haskins Laboratories. A test tape was then recorded, containing 20 trials of each natural token in randomized order for a total of 120 test trials. A pause of 3 s occurred between trials, and a pause of 10 s occurred every six trials.

Procedure. Subjects, run in groups of 2 to 5, listened to the tape binaurally through headphones. They were told that they would be hearing recordings of objects that had either bounced or broken after being dropped but were told nothing about the nature of the objects involved. Their three-choice task was to categorize each event as a case of breaking or bouncing, with a *don't know* option, by placing a check in the appropriate column on an answer sheet. To minimize the possibility that they would choose one of the two event categories if they found the sound unconvincing, subjects were instructed to use the *don't know* category if they could not make up their minds, if they could not tell what the event was, or if it sounded like some other type of event. They were specifically instructed to ignore the nature of the object involved and attend to "what's happening to it". Subjects received no practice trials or feedback. There was a short break after 60 trials, and a test session lasted about 20 min.

Results and Discussion

Overall performance on natural bouncing tokens was 99.3% correct ("bouncing" judgments), and on breaking tokens was 98.5% correct ("breaking" judgments). *Don't know* responses accounted for 0.2% of all answers on bouncing tokens and 0.7% on breaking tokens. Experiment 1 demonstrates that sufficient information exists in the acoustic signal to permit unpracticed listeners to categorize the natural events of bouncing and breaking, at least within the limits of the three-choice task.

This successful categorization could be based on various temporal and spectral properties of the signal, as discussed in the introduction. Although the bouncing tokens were all of longer duration than were the breaking tokens, duration is a function of object elasticity and height of drop and does not provide reliable information specific to a style of change. Both spectral properties and token duration were controlled in Experiment 2 to isolate the effect of temporal patterning.

Experiment 2: Constructed Tokens

In Experiment 2 we attempted to model the time-varying information contained in natural recording by using constructed cases of bouncing and breaking, eliminating average spectral differences between the two.

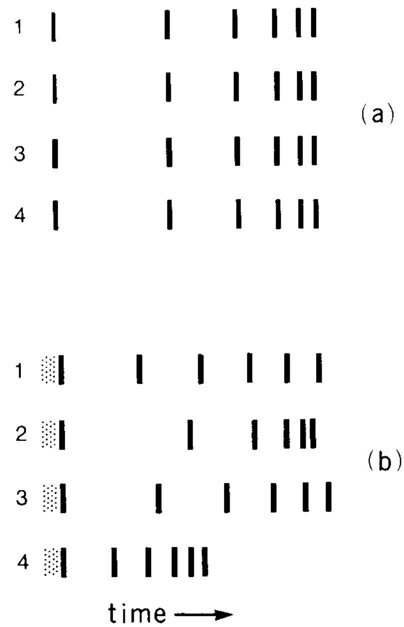

Figure 3 Schematic diagrams of constructed tokens, combining four component pulse trains: (a) bouncing, with synchronous pulse onsets; (b) breaking, with initial noise burst and asynchronous pulse onsets. (Each pulse train has unique spectral properties.)

Method

Subjects. Fifteen graduate and undergraduate students participated in the experiment for payment or course credit. None of them had participated in Experiment 1.

Materials. Tokens intended to model bouncing and breaking were constructed by the following method. Initially, individual recordings were made of four major pieces of glass from a broken bottle as each piece was dropped and bounced separately from a low height. These recordings were combined in two ways using the PCM system.

To construct an artificial bouncing token, the temporal pattern of the recording of each piece was adjusted to match a single master periodicity arbitrarily borrowed from a recording of a natural bouncing bottle (Figure 3a). This was accomplished by inserting silence between the bounce pulses in recordings of the individual pieces. After the recordings of all four pieces had been adjusted so that their onsets matched the same pulse pattern, they were superimposed by summing the instantaneous amplitudes of the digitized recordings. The result was a combined pulse pattern with *synchronized* onsets for all bounces, preserving the invariant of a single damped quasi-periodic pulse train to model bouncing (Figure 4a).

An artificial breaking token was constructed by readjusting the recordings of the same four pieces to match four different temporal patterns (Figure 3b). As a first approximation, these master patterns were borrowed from measurements of four different bouncing bottles, because the likely patterns of individual pieces of glass in the course of natural breaking were unknown. These four patterns were initiated simultaneously, preceded by 50 ms of noise burst taken from the original rupture that produced the four pieces of glass. The result after superimposing these four independent temporal series was a combined pattern with *asynchronous* pulse onsets, preserving the temporal invariant of multiple damped quasi-periodic pulse trains to model breaking (Figure 4b). Note that the variables of temporal patterning and initial noise were confounded in this experiment. To the experimenters' ears the burst improved the quality of apparent breakage, but this assumption was later tested.

Three constructed cases of bouncing and three corresponding cases of breaking were produced by this method, each pair constructed from a unique set of recordings of original pieces and matched to a unique set of master periodicities. To help assure the generality of the method, the first three pairs constructed in this manner were used in the experiment. The original objects, and the durations of the bouncing or synchronous (SYN) and breaking or asynchronous (ASYN) tokens constructed from their pieces, were as follows: (a) 32-oz (0.946 l) jar: SYN1 = 1,000 ms, 8 collisions; ASYN1 = 950 ms. (b) 32-oz (0.946 l) jar: SYN2 = 1,400 ms, 13 collisions; ASYN2 = 650 ms. (c) 64-oz (1.892 l) bottle: SYN3 = 920 ms, 9 collisions; ASYN3 = 600 ms.

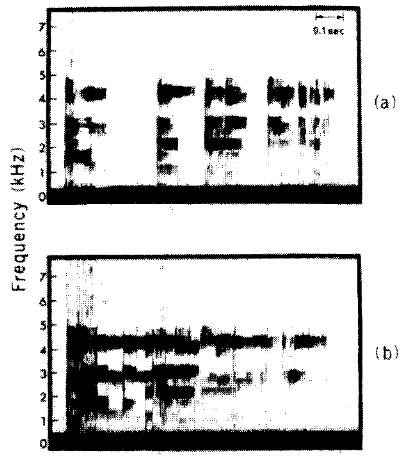

Figure 4 Spectrograms of constructed tokens: (a) bouncing (SYN1); (b) breaking (ASYN1).

Hence, the only differences between constructed bouncing and breaking tokens were in the temporal registration of pulse onsets and the presence (or absence) of initial noise. The range and distribution of spectral frequencies, averaged over time, were comparable in the two cases. Tokens SYN1, SYN3 and ASYN1 had similar durations of 920 to 1,000 ms, and thus if subjects based categorization on this factor, large errors should occur with these tokens.

There were certain problems with the constructed cases. The process of superimposing pulse patterns also summed tape hiss and hum so that background noise was increased. Moreover, using recordings of only four large pieces of glass concentrated more spectral energy in the lower frequency ranges as compared to natural tokens (cf. Figures 2 and 4), and constructing the sound of a single bouncing object by combining the spectral components of these four pieces produced two tokens that sounded more like metal than like glass material (SYN1 and SYN2). Nevertheless, the temporal invariant was preserved. Finally, the use of only four pieces of glass to model breaking, the assumption that their periodicities were akin to those of whole bouncing bottles, and the assumption of no further breakage after the initial catastrophe, were all rather arbitrary idealizations. Nevertheless, if temporal patterning constitutes sufficient information for breaking and bouncing, subjects should be able to make reliable judgments of these tokens.

Token	Bouncing	Breaking
1		
%	93.7	89.0
M	18.7	17.8
SD	1.7	2.9
2		
%	94.3	71.3
M	18.9	14.3
SD	2.0	4.3
3		
%	84.3	99.7
M	16.9	19.9
SD	3.7	0.3
Overall %	90.7	86.7

Note. Scores are based on 20 trials per subject per cell, $N = 15$.

Table 1 Percentage of trials in which constructed tokens of bouncing and breaking were categorized as such (Experiment 2).

Procedure. The procedure was the same as that in Experiment 1. Instructions to the subjects were the same, including the instruction to ignore object properties and concentrate on the style of change.

Results and Discussion

The results for each constructed token appear in Table 1 and are consistent with the predictions of the temporal patterning hypothesis. Bouncing judgments on synchronous tokens averaged 90.7%, and breaking judgments on asynchronous tokens averaged 86.7% (theses judgments being treated as correct). *Don't know* answers accounted for 0.1% of all responses on bouncing tokens and 1.3% on breaking tokens. Considering the artificial nature of the constructed cases and the idealizations involved, this performance may be considered quite high.

The absence of any large systematic decrement for tokens SYN1, SYN3, and ASYN1 indicates that subjects were not relying on simple duration in making their judgments. Some departures from the general pattern were found for token ASYN2, which showed markedly lower performance (71.3%), a higher intersubject standard deviation, and a relatively high rate of *don't know* responses (4.0%). These differences were primarily due to the low performance of 5 subjects who averaged 44% on this token, whereas the performance of the other 10 averaged 85%. It may be noted that the summed backround noise was greater in ASYN2 than in the other two breaking cases. The fact that overall performance in this case was well above chance indicates that even the poorest token contained usable information. It is not surprising that some tokens of constructed breaking are more convincing than others, because there are certainly some natural instances that are more compelling than others. The differences among tokens may involve both the spectral distinctiveness of the component pieces of glass and their degree of asynchrony.

In general, performance with constructed tokens was well above the chance level, similar to that found for natural tokens in Experiment 1. Performance with constructed cases was only about 10% lower than with natural cases, despite the summation of noise, the idealizations of construction, and the metallic sound of tokens SYN1 and SYN2. The data permit us to conclude that temporal patterning with initial noise provides sufficient information for listeners to categorize breaking and bouncing events. A subsequent experiment (Warren & Verbrugge, 1984) showed that, given these two types of events, the variation in temporal pattern alone without the initial noise burst is a sufficient discriminator. Further work remains to be done, however, to determine whether the initial noise is necessary for identifying breakage under conditions less constrained than those in the present experiment.

General Discussion

In the preceding experiments we have attempted to determine whether higher order, time-varying properties constitute effective acoustic information for the events of bouncing and breaking. The results show that certain damped periodic patterns provide sufficient information for listeners to discriminate the two events, without significant differences in average spectral properties.

The strength of the results is mitigated by the limitations of the three-choice categorization task. By definition, the task requires foreknowledge of the event classes and does not exclude the possibility that a token may be categorized as *breaking* because it sounds something *like* that event, even though it would not uniquely convey breaking outside the restricted conditions of the experiment. Although a free identification task might test this possibility, the tokens were not constructed to fully simulate real events of breaking and bouncing glass, as evidenced by the metallic sound of bouncing tokens SYN1 and SYN2 and the use of only four component pieces to construct breaking tokens. Successful simulation would require still more complex manipulations of acoustic structure, including spectral information for the material composition of the object, predicated on findings such as those reported here.

The amplitude and periodicity requirements of the temporal patterns in bouncing vents were considered in two simple demonstrations worth mentioning here. Iterating a recording of one bounce pulse to match the timing of a natural bouncing sequence produced a clear bouncing event, although the usual declining amplitude gradient was absent. However, adjusting the pulse pattern to create equal 100-ms intervals between pulse onsets, thereby eliminating the damping of the periodic pattern, destroyed the effect of perceived bouncing, even with a declining amplitude gradient. The rapid staccato sound was like that produced by a machine, such as a jackhammer. A damped series of collisions, constrained by gravity and the imperfect elasticity of the system, appears necessary to the information for bouncing, as originally hypothesized. Experiments are in progress to assess the efficacy of period damping as information for elasticity or "bounciness" itself.

Further research is needed to determine the acoustic patterns necessary to specify single and multiple pulse trains. As suggested in the original hypotheses, distinct spectral properties for each asynchronous pulse train in a breaking token may be required to segregate the pulse trains and convey the existence of separate pieces of glass (although the superimposition of *synchronous* pulse trains with different frequency spectra did not yield the perception of separate pieces in the bouncing tokens). Reciprocally, it may be necessary for the successive pulses of a bouncing token to be spectrally similar in order to convey the unity of the pulse train and to cohere as the bouncing of a single object.

The present experiments exemplify an ecological approach to auditory perception, seeking to identify higher order acoustic information for environmental events. The acoustic consequences of two distinct types of mechanical events were analyzed for their temporal and spectral structure, and some time-varying properties sufficient to convey aspects of the events to a listener were empirically determined. Such work is preliminary to modeling auditory mechanisms capable of identifying acoustic events and sources in the world.

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*The first author is now at the W.S. Hunter Laboratory of Psychology, Brown University.