Research Article

NATURAL MUSICAL INTERVALS: Evidence From Infant Listeners

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Abstract—*Ancient and medieval scholars considered tones related by simple (small-integer) ratios to be naturally pleasing, but contemporary scholars attribute the special perceptual status of such sounds to exposure. We investigated the possibility of processing predispositions for some tone combinations by evaluating infants' ability to detect subtle changes to patterns of simultaneous and sequential tones. Infants detected such changes to pairs of pure tones (intervals) only when the tones were related by simple frequency ratios. This was the case for 9-month-old infants tested with harmonic (simultaneous) intervals and for 6-month-old infants tested with melodic (sequential) intervals. These results are consistent with a biological basis for the prevalence of particular intervals historically and cross-culturally.*

The origin of the idea that consonant, or pleasant-sounding, combinations of musical tones have special numerical properties is generally attributed to Pythagoras (ca. 600 BC) (see Plomp & Levelt, 1965, for a review of historical accounts of consonance and dissonance). When Pythagoras partitioned a vibrating string into two sections whose lengths were related by simple (i.e., small-integer) ratios, such as 2:1, 3:2, and 4:3, he observed that the resulting combinations of tones sounded more consonant than did combinations for lengths related by more complex ratios. In the Middle Ages, beauty in general was considered to depend on numerical properties, music in particular being "number made audible" (Seay, 1975, p. 19). Indeed, the medieval philosopher Boethius considered music, arithmetic, geometry, and astronomy to be equal parts of the Quadrivium, the four essential disciplines of mathematics. The degree of beauty was believed to reflect the relative simplicity of the underlying numerical relations. In fact, musical intervals (combinations of two tones) with simple ratios were thought to mirror the beauty of God, the complex-ratio (45:32) interval known as the *tritone* being the "devil in music" (Seay, 1975, p. 83).

Renaissance scholars' discovery of the association between the pitch of a tone and its frequency of vibration (hertz, or cycles per second) provided a psychophysical rationale for Pythagorean ideas of consonance—subdividing a string into simple ratios based on length results in simple ratios based on frequency (see Hall, 1980, p. 442). According to Galileo (17th century) as well as some contemporary theorists (Bernstein, 1976; Boomsliter & Creel, 1961), tones related by simple frequency ratios are preferred because their vibrations generate more regular or pleasing neural patterns, a claim as yet uncorroborated (Burns & Ward, 1982). Nevertheless, the discovery that most naturally occurring tones contain multiple component tones whose frequencies are related by simple ratios, such as 2:1, 3:2, and 4:3, was considered by Rameau (18th century) to be sufficient evidence for their special status. For example, a tone complex with a fundamental frequency of 100 Hz has overtones (or additional harmonics) of 200 Hz, 300 Hz, 400 Hz, and so on.

Helmholtz (1885/1954), in the late 19th century, refined the argument, providing the basis for contemporary explanations of *sensory consonance* as a function of critical bandwidth (Kameoka & Kuriyagawa, 1969a, 1969b; Plomp & Levelt, 1965). Whereas sensory consonance results from natural or psychoacoustic properties, *musical consonance* is considered to have cultural origins. The essence of the current view of sensory consonance is that tone complexes related to one another by simple ratios have more overtones in common than tone complexes related by complex ratios; in the latter case, overtones that are proximate but not identical in pitch are more likely to fall within the same critical band, resulting in amplitude fluctuations and the perception of roughness or dissonance. Terhardt (1978, 1984), mindful that explanations of this kind are limited to the sensory consonance of complex tones sounded simultaneously, suggested that listeners' knowledge of the frequency ratios between components of complex tones might be generalized to auditory processing in other contexts, including those involving sequential tones or simultaneous pure tones. Nevertheless, the prevailing view is that the special status of tones related by simple frequency ratios stems largely from exposure to a particular musical culture or style (Burns & Ward, 1982; Dowling & Harwood, 1986; Serafine, 1983) and is, therefore, a reflection of musical consonance.

The purpose of the present study was to explore the possibility that the special perceptual status of intervals (tone combinations) with simple frequency ratios has a natural or biological basis, in line with suggestions from ancient and medieval philosophers. The tones that make up an interval can be sounded simultaneously, forming a *harmonic* interval, or sequentially, forming a *melodic* interval. The notion of an inherent perceptual bias for simple frequency ratios is contentious. Because simple frequency ratios are structurally important in Western music, suggestions of their universality (Bernstein, 1976) are often interpreted as ethnocentric (Dowling & Harwood, 1986). Some 20th-century music theorists and composers have gone so far as to suggest that all scale structures are equally learnable (or natural), even those that deny a privileged role for simple frequency ratios. For example, it was Schoenberg's contention that modern atonal music, despite its paucity of simple ratios, would ultimately become a musical language as universal as Western tonal music (Lester, 1989). How, then, can one account for the occurrence of the simplest frequency

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ratios, such as 2:1, 3:2, and 4:3, in the scales of musical cultures that exhibit the greatest differences?

Not only are octaves (intervals with a frequency ratio of 2:1) considered to be musical universals, but the perceptual similarity of tones an octave apart is thought to be the only property of intervals that is attributable to the structure of the auditory system (Dowling & Harwood, 1986). In Chinese (Koon, 1979), Indian (Capwell, 1986; Jairazbhoy, 1971), Javanese (Hood, 1954; Lentz, 1965), and Thai (Morton, 1980) music, however, intervals approximating a 3:2 ratio (i.e., *perfect fifths*) are also structurally significant. Moreover, many musical traditions accompany their melodic line with a drone consisting of the tonic (i.e., reference or key tone) and the tone a perfect fifth higher (Lerdahl & Jackendoff, 1983), reflecting the prominence of the 3:2 ratio.

Further support for the natural or biological imperative is provided by the 20th-century discovery and decoding of an ancient Near Eastern song dated approximately 1400 BC (Kilmer, Crocker, & Brown, 1976). To the astonishment of many scholars, the song, which is at least 1,000 years older than any other known song, is anything but exotic. Instead, it sounds uncannily familiar, with its simple frequency ratios between component tones. Furthermore, the accompanying lyre, whose strings are thought to have been tuned to simple frequency ratios (West, 1994), produces simultaneous tones (between voice and lyre) that are also related by simple frequency ratios (Kilmer et al., 1976).

If intervals with simple frequency ratios are natural in some sense, then naive listeners such as infants should exhibit enhanced processing for such intervals relative to intervals with complex frequency ratios. Demany and Armand (1984) demonstrated that infants perceive tones an octave apart (standing in a 2:1 ratio) to be more similar than tones slightly more than or slightly less than an octave apart. In the present study, we explored the possibility that simple frequency ratios in general have special status for young infants. We know that adults exhibit processing advantages for melodic intervals whose component tones are related by simple ratios, even with pure tones (i.e., no simultaneous cues to consonance and dissonance) presented in nonmusical contexts (i.e., reduced influence of musical knowledge). Specifically, adults readily differentiate a standard tone sequence with a simple frequency ratio from a comparison sequence with a more complex ratio, but they have difficulty differentiating a standard sequence with a complex ratio from a comparison sequence with a simpler ratio (Schellenberg & Trehub, 1994a). We have demonstrated (Schellenberg & Trehub, 1994b), moreover, that the relative simplicity of frequency ratios provides a parsimonious account of all available data on the perception of musical intervals. The possibility remains, however, that these findings with adult listeners are attributable to implicit knowledge of Western scale structure, acquired by incidental exposure to music over many years.

Six-year-old children who have never taken music lessons show comparable asymmetries in discrimination, detecting changes from simple to complex frequency ratios but failing to detect changes from complex to simple ratios (Schellenberg & Trehub, in press). Because simple frequency ratios are structurally important in Western music, however, incidental exposure may still be implicated. Similar processing biases on the part of prelinguistic listeners would provide a stronger case against explanations based simply on exposure.

The available evidence on melodic discrimination in infancy is consistent with processing biases for simple frequency ratios. For example, infants perform better on tone sequences with a perfect fifth interval (3:2 ratio) than on sequences without this interval (Cohen, Thorpe, & Trehub, 1987; Trainor & Trehub, 1993a, 1993b; Trehub, Thorpe, & Trainor, 1990). Nevertheless, the effect of simple and complex frequency ratios on infants' discrimination of simultaneous or sequential tones has not been examined directly. We assumed that ease of processing a standard tone pattern would translate to enhanced discrimination of a comparison pattern, as was the case for adult and child listeners (Schellenberg & Trehub, 1994a, in press). Moreover, if the special status of simple frequency ratios for adult and child listeners has its basis in fundamental properties of the auditory system rather than musical exposure, then infants should show preferential processing of simultaneous and sequential patterns of pure tones related by simple frequency ratios.

EXPERIMENT 1

In this experiment, we evaluated infants' ability to detect subtle changes to harmonic intervals (simultaneous pairs of tones) whose component tones were related by simple or by complex frequency ratios. The use of pure tones (sine waves) sufficiently distant in pitch precluded the possibility of amplitude fluctuations from tones within a common critical band. Hence, differential performance in the context of patterns with simple as opposed to complex frequency ratios could not be attributable to differences in sensory consonance, as currently defined.

Method

Participants

The participants were 36 infants 8.5 to 9.5 months of age (mean age of 8 months, 27 days), none of whom had a family history of hearing impairment, a personal history of ear infections, or a cold on the day of testing. An additional 10 infants were tested but excluded from the final sample because of failure to meet the training criterion (n = 4), crying or fussing (n = 5), or parental interference (n = 1).

Stimuli

Each pattern consisted of a single interval of two pure tones (sine waves) sounded simultaneously for 750 ms, with 10-ms rise and decay times (see Fig. 1). Consecutive patterns were separated by a 250-ms silence. The low tone was fixed at middle C (C_4, or 262 Hz) across all conditions and trials. The high tone of the standard (background) pattern was 7, 6, or 5 semitones above the low tone: G_4 (392 Hz) in the 3:2 condition, $F_4^{\#}$ (368 Hz) in the 45:32 condition, or F_4 (349 Hz) in the 4:3 condition, respectively (equal-tempered tuning). In each condition, the contrasting pattern was formed by reducing the frequency of the high tone by one quarter of a semitone (i.e., multiplying by a factor of 0.986). During the training phase, however, the high

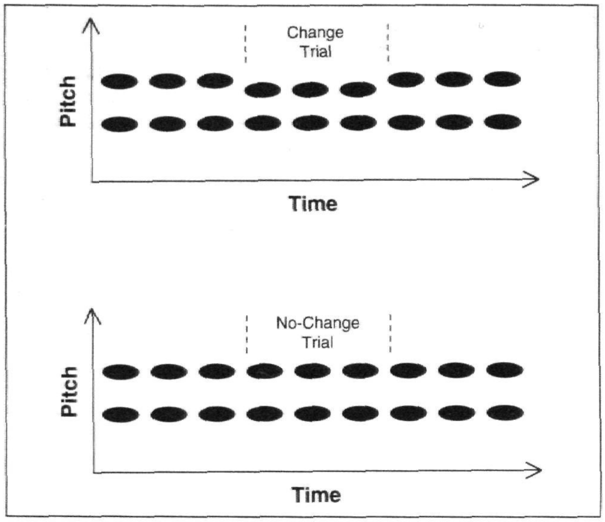

Fig. 1. Schematic illustration of the procedure for evaluating infants' discrimination of harmonic (simultaneous) intervals (Experiment 1). Repetitions of the standard harmonic interval are followed by a change trial (upper panel) in which the top tone of the interval is displaced downward by ¼ semitone (not drawn to scale) for three repetitions, followed by a return to the standard interval. On no-change trials (lower panel), which are equivalent in duration to change trials, the standard interval continues to be presented.

tone of the contrasting pattern was 4 semitones higher than the tone it replaced.

Design and procedure

Each infant was assigned to one of three conditions based on the frequency ratio between the tones of the repeating background pattern. The standard patterns in two conditions had simple ratios—3:2 (perfect fifth, 7 semitones) and 4:3 (perfect fourth, 5 semitones); the standard pattern in the third condition had a complex ratio—45:32 (tritone, 6 semitones). Because one simple-ratio interval was larger (7 semitones) and one smaller (5 semitones) than the complex-ratio interval (6 semitones), the design separated possible effects of ratio simplicity from those of interval magnitude.

Infants were tested individually with an operant head turn procedure (e.g., Trehub & Trainor, 1993) in a double-walled, sound-attenuated booth. Stimulus presentation and response recording were computer controlled. Infants sat on a parent's lap facing the experimenter and heard the standard (background) tone pattern presented repeatedly from a loudspeaker located 45° to their left. During the training and test phases, correct head turns to the loudspeaker (hits) that occurred within a 3-s response window during presentation of a contrasting pattern resulted in visual reinforcement, which consisted of illumination and activation of a mechanical toy for 2 s. Turns at other times (false alarms) had no consequence. Because the principal purpose of training was to familiarize infants with the procedure, differences between the standard and contrasting patterns (see Stimuli) were considerably greater in the training than in the test phase (for further procedural details, see Trainor & Trehub, 1993a, 1993b). Infants were required to meet a criterion of five consecutive correct responses (head turns) within a maximum of 30 trials before proceeding to the test phase.

During the test phase, as in the training phase, the experimenter indicated when the infant was facing directly forward and "ready" for a trial (by pressing a button) and when the infant turned to the loudspeaker (by pressing another button). Trials were of two types (see Fig. 1): change trials, consisting of three presentations of the contrasting pattern (same amplitude as the background pattern), and no-change trials, consisting of three presentations of the standard pattern. During both kinds of trials, head turns were monitored for 3 s. Parent and experimenter wore headphones with masking music, which obscured the distinctions between change and no-change trials. Consecutive trials were separated by a minimum of six repetitions of the pattern. Equal numbers of change and no-change trials were presented in pseudorandom order, constrained by a limit of no more than 2 consecutive no-change trials. This constraint precluded the occurrence of several consecutive no-change trials with no possibility of reinforcement, which might lead the infant to lose interest. The test phase of each condition had 30 trials (15 change, 15 no-change).

Results and Discussion

For each infant, a discrimination (d') score (Elliott, 1964) was derived from the number of hits (correctly turning on change trials) and false alarms (incorrectly turning on no-change trials). Following Thorpe, Trehub, Morrongiello, and Bull (1988), the data were transformed to avoid spurious (infinite) d' scores arising from perfect performance.

Infants succeeded in detecting changes to the 3:2 and 4:3 intervals but not to the 45:32 interval. That is, their d' scores were significantly above chance levels ($d' = 0$) in the 3:2 condition, $t(11) = 4.88$, $p < .001$, and in the 4:3 condition, $t(11) = 3.69$, $p = .004$, but not in the 45:32 condition, $t(11) = 0.752$, $p = .468$ (see Fig. 2). An analysis of variance indicated that the difference across conditions was statistically reliable, $F(2, 33) = 3.34$, $p = .048$, with planned orthogonal comparisons revealing higher performance levels in the 3:2 and 4:3 conditions than in the 45:32 condition, $F(1, 33) = 5.69$, $p = .023$, but no difference between the 3:2 and 4:3 conditions, $F < 1$.

Thus, infants could more readily detect changes to simultaneous intervals with simple frequency ratios than to simultaneous intervals with more complex ratios. The results are consistent with processing predispositions favoring simple frequency ratios over more complex ratios. Nevertheless, it is impossible to entirely rule out effects of exposure as an explanation of these results. The simultaneous components of vocal and nonvocal sounds in the natural environment are related by simple frequency ratios. As a result, sounds with simple-ratio components are heard more frequently by listeners of all ages than are sounds with complex-ratio components. By contrast, sequences of natural sounds, spoken or otherwise, have no such constraints on the ratio relations of their fundamental frequencies, except when conceived as music. Indeed, the cele-

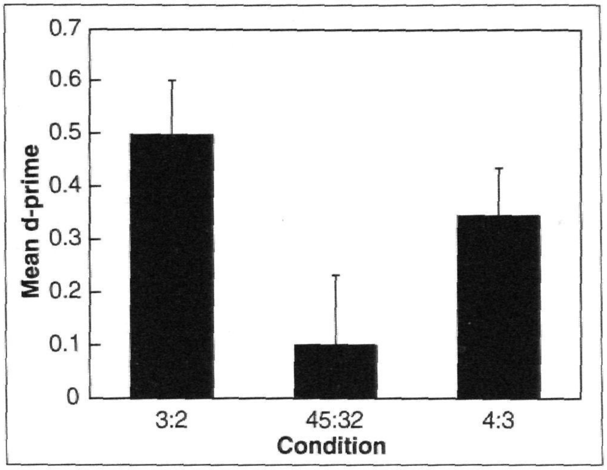

Fig. 2. Mean discrimination (d') scores as a function of the frequency ratio of tones in the standard harmonic (simultaneous) interval (Experiment 1). Error bars represent standard errors.

brated melodies of maternal speech (Fernald, 1989) do not conform to tonal conventions. Thus, a stronger test of the hypothesis of natural intervals would require the use of melodic, or sequential, intervals.

EXPERIMENT 2

In this experiment, we evaluated infants' discrimination of sequential tone patterns (melodic intervals), which provided a stricter test of the hypothesis of processing advantages for simple frequency ratios. As a further attempt to limit the "musical experience" of infants, we targeted the youngest age that could be effectively tested with the current procedure—approximately 6 months. We expected that changes to melodic intervals with simple frequency ratios would be easier to detect than changes to melodic intervals with more complex ratios, as was the case for the harmonic intervals (simultaneous tones) in Experiment 1.

Method

Participants

The 54 participants were 6- to 7-month-old infants (mean age of 6 months, 21 days), who were selected according to the criteria outlined for Experiment 1. An additional 13 infants were excluded from the final sample for failing to meet the training criterion ($n = 4$), crying or fussing ($n = 5$), or parental interference ($n = 4$).

Stimuli

In all conditions, the standard (background) pattern consisted of eight alternating pure tones (low-high-low-high-low-high-low-high), each 500 ms in duration (10-ms rise and decay). The standard pattern was presented repeatedly, with consecutive presentations transposed upward or downward by 2 semitones. In the lowest possible transposition, the low and high tones of the 7-semitone (3:2) standard stimulus were 300 and 450 Hz; those of the 6-semitone (45:32) and 5-semitone (4:3) standards were 300 and 422 Hz, and 300 and 400 Hz, respectively (just tuning). Other possible transpositions were 2, 4, 6, 8, and 10 semitones higher. In all three conditions, a contrasting pattern was formed by displacing the second and sixth tones of the pattern (i.e., the first and third high tones) downward by a semitone (frequency multiplied by approximately 0.944) (see Fig. 3). During the training phase, the contrasting pattern was formed by doubling the frequency of alternate high tones so that they were an octave above the tones they replaced.

Design and procedure

There were three conditions, with 18 infants assigned to each. In two conditions, the standard pattern had a simple frequency ratio (3:2 or 4:3) between high and low tones; in the third condition, the standard pattern had a complex ratio (45:32). Because the interval of the standard pattern with a simple ratio was either larger (7 semitones, 3:2 condition) or smaller (5 semitones, 4:3 condition) than the interval of the standard pattern with a complex ratio (6 semitones, 45:32 condition), the design separated effects of interval magnitude from those of ratio simplicity.

Infants proceeded to the test phase after achieving four con-

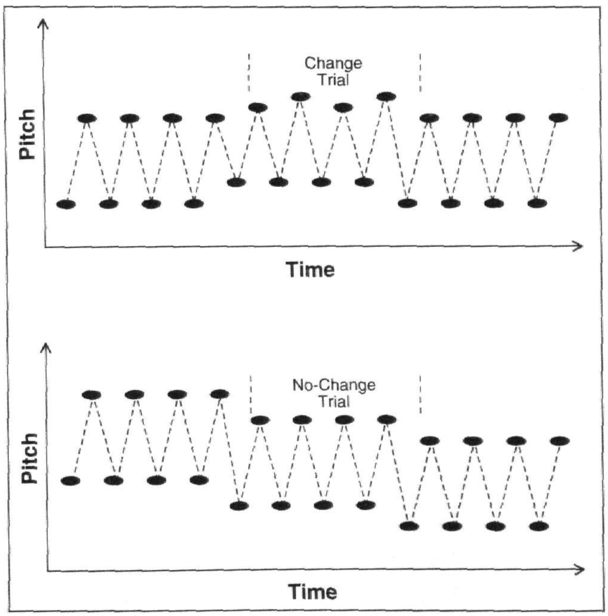

Fig. 3. Schematic illustration of the procedure for evaluating infants' discrimination of melodic (sequential) intervals (Experiment 2). The standard pattern consists of eight alternating low and high tones that repeat in transposition. Alternate high tones are displaced downward by a semitone (not drawn to scale) on change trials (upper panel) but not on no-change trials (lower panel), both of which consist of a single presentation of the eight-tone pattern.

secutive correct responses during the training phase (within a maximum of 20 trials). Head turns were scored during a 4-s response window on change and no-change trials. Turns on change trials resulted in visual reinforcement (3 s); turns on no-change trials had no consequence. In the test phase of each condition, infants received 12 change trials, each of which consisted of one presentation of the contrasting pattern, and 12 no-change trials, each of which consisted of one presentation of the standard (repeating background) pattern. In all other respects, the procedure was identical to that of Experiment 1.

Results and Discussion

As in Experiment 1, a discrimination score (d') was derived separately for each infant. Infants succeeded in discriminating the contrasting pattern from the repeating background pattern when the latter had a simple frequency ratio, performing reliably better than chance levels in the 3:2 condition, $t(17) = 3.94$, $p = .001$, and in the 4:3 condition, $t(17) = 3.82$, $p = .001$ (see Fig. 4). Performance was no better than chance, however, when the standard pattern had a complex 45:32 ratio, $t(17) = 0.374$, $p = .713$. An analysis of variance revealed that performance was significantly different across conditions, $F(2, 51) = 3.99$, $p = .025$. Orthogonal contrasts indicated that the difference was due to performance being more accurate in the simple-ratio conditions than in the complex-ratio condition, $F(1, 51) = 7.65$, $p = .008$; performance did not differ between the two simple-ratio conditions, $F < 1$. Hence, the superior performance for simple relative to complex ratios in the context of harmonic intervals (Experiment 1) extends to even younger listeners and to melodic intervals comprising pure tones.

GENERAL DISCUSSION

Infants exhibit perceptual biases for simple frequency ratios well before their first birthday. Their perception of tone patterns with simple or complex frequency ratios is consistent with data from adult listeners (Schellenberg & Trehub, 1994a, 1994b) and child listeners (Schellenberg & Trehub, in press), and with the intuitions of ancient and medieval scholars. It is inconsistent, however, with contemporary psychoacoustic accounts of consonance and dissonance, which rely exclusively on listeners' perception of amplitude fluctuations from tones that fall within the same critical band (Kameoka & Kuriyagawa, 1969a, 1969b; Plomp & Levelt, 1965). Such explanations are irrelevant to the simultaneous and sequential pure tones of the present study, which were sufficiently distant in pitch to preclude such effects. Thus, the finding that intervals with simple frequency ratios have special status for infant listeners necessitates a redefinition of sensory (natural) consonance as a joint function of frequency ratio and frequency distance (critical bands).

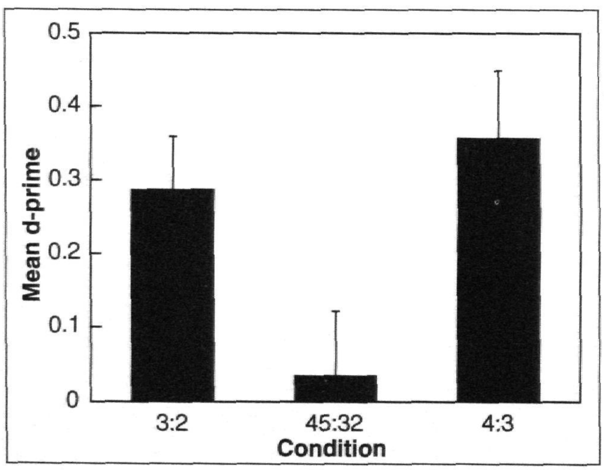

Fig. 4. Mean discrimination (d') scores as a function of the frequency ratio of tones in the standard melodic (sequential) interval (Experiment 2). Error bars represent standard errors.

The use of child (Schellenberg & Trehub, in press) and adult (Schellenberg & Trehub, 1994a) listeners in previous investigations of interval perception precluded unequivocal attribution of the observed performance asymmetries to nature (i.e., predispositions) as opposed to culture (i.e., exposure). In the present study, however, listeners' tender age reduced potential contributions from musical enculturation. Even if these infants managed to learn about simple frequency ratios from co-occurring sounds in their natural environment, this accomplishment would surely reflect innate attentional preferences (Marler, 1990) for sounds with simple ratios (Terhardt, 1978, 1984). Accordingly, the most parsimonious interpretation of the present findings is an inherent bias for the perception of tones whose frequencies are related by simple ratios. Our suggestion of processing predispositions for simple frequency ratios is entirely consistent with the dominance of musical scales with simple frequency ratios throughout history and across cultures.

Our findings may offer some insight into the typically negative reactions to contemporary atonal music. Although mere exposure is an important contributor to "liking" (Moreland & Zajonc, 1977), it cannot be the only relevant factor. Otherwise, music teachers would, paradoxically, derive ever-increasing pleasure from the repeated blunders of their students (Gaver & Mandler, 1987). On the basis of the present findings, we would argue that the paucity of simple ratios in 20th-century atonal music contributes to the "difficulty" of such music (i.e., the difficulty of perceiving its structure), a situation exacerbated by complex rhythmic and metrical structures and greatly reduced information redundancy (Lerdahl & Jackendoff, 1983; Meyer, 1994). We do not claim that there are immutable barriers to such music becoming pleasing. Rather, systematic learning and exposure would be required to transform the initially incomprehensible and disliked into the newly understood and enjoyable (Gaver & Mandler, 1987; Lerdahl & Jackendoff, 1983). Perhaps atonal music is the "exception that proves the rule": Avant garde composers might have no need to violate the "comfortable" tonal framework were it not so comfortable.

But why do simple frequency ratios have special status for human listeners? Perhaps people are preferentially sensitive to the spectral structure of speech sounds (Terhardt, 1978, 1984), the simultaneous components of which are related by simple ratios. Indeed, the adaptive significance of speech makes such preferential sensitivity plausible, to say the least. Alternatively, intervals with simple frequency ratios may be natural prototypes (Rosch, 1975), being relatively easy (compared with complex-ratio intervals) to encode, retain, and distinguish from other intervals. One can only marvel at the prescience of Pythagoras and Boethius!

Acknowledgments—This research was supported by the Natural Sciences and Engineering Research Council of Canada. We thank Morris Moscovitch and Bruce Schneider for their comments on an earlier draft of the manuscript.

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(RECEIVED 4/28/95; ACCEPTED 8/14/95)