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Effect of Frequency Ratio on Infants' and Adults' Discrimination of Simultaneous Intervals

Laurel J. Trainor
McMaster University

Effects of frequency ratio simplicity on infants' and adults' processing of simultaneous pitch intervals with component sine wave tones were tested. Both infants and adults showed superior performance at detecting a change from a perfect 5th (2:3) to either a tritone (32:45) or a minor 6th (5:8) interval than at detecting the reverse discriminations (minor 6th or tritone to perfect 5th). Similarly, both infants and adults showed superior performance at detecting a change from an octave (1:2) to either a major 7th (8:15) or a minor 9th (15:32) interval than at detecting the reverse discriminations. In combination with previous findings of infants' superior discrimination of tone sequences with prominent perfect 5th intervals, these results suggest that both simultaneous and sequential intervals with simple ratios are easy to process early in development.

Pitch intervals (i.e., pitch distance between two tones on a log frequency scale) whose component tones stand in small-integer frequency ratios (e.g., octave interval, 1:2; perfect fifth interval, 2:3) are perceptually special for Western adults in that they are rated as most consonant (i.e., pleasant), and their component tones are judged to be more similar than those of pitch intervals with more complex ratios (e.g., see Plomp & Levelt, 1965; Schellenberg & Trehub, 1994b). Recent evidence indicates that melodic patterns (i.e., sequences of successive tones) with prominent perfect fifth or octave intervals are perceptually special for infants as well for adults (Cohen, Thorpe, & Trehub, 1987; Demany & Armand, 1984; Trainor & Trehub, 1993a). In the experiments reported here, I examined whether infants and adults also show similar perceptual effects for simultaneous octave and perfect fifth intervals composed of sine wave tones. In simultaneous presentation, the two tones composing the pitch interval are sounded at the same time rather than sequentially.

An examination of the different musical systems used in various cultures reveals that melody, involving sequential intervals, is the primary dimension of musical pitch structure (Dowling & Harwood, 1986). In virtually all musical systems, melodies comprise a small set of discrete pitches (usually five to seven) per octave called scales. However, harmony, or simultaneous tone structure, may be unique to Western music. Western melodies have implied harmonies: Listeners expect particular chords (i.e., three or more simultaneous tones) to harmonize or accompany different notes of the melody. Trainor and Trehub (1994) suggested that the universality of melody in comparison to harmony might indicate that it is easier to learn melodic than harmonic structure. In line with this suggestion, they found that whereas knowledge of key membership (i.e., which notes belong to the scale in which a melody is composed and which do not) is well established by 5 years of age, knowledge of implied harmony does not emerge until 7 years of age. This raises the possibility that the perceptual effects of small-integer frequency ratios in simultaneous intervals may arise considerably later in development than do those in melody. Alternatively, such effects in simultaneous intervals may be evident relatively early on, even though sensitivity to musical harmony requires years to develop. In these experiments, I tested whether perceptual effects of small-integer frequency ratios in simultaneous intervals can be demonstrated in 6- to 8-month-olds infants and in adults.

Recent studies have shown that both infants and adults find it much easier to discriminate a small change to one note of a melodic pattern with a prominent perfect fifth pitch interval (i.e., a 2:3 ratio) than to a melodic pattern without this feature, regardless of whether the patterns conform to Western musical structure (Cohen et al., 1987; Trainor & Trehub, 1993a) or not (Trainor & Trehub, 1993b). Further, the effect of the perfect fifth interval can also act at relatively global levels. Both infants and adults find it easier to compare short melodies transposed (i.e., shifted up or down in pitch, such that all pitch intervals between tones remain the same) by perfect fifth intervals than by intervals with more complex ratios between their component tones (Trainor & Trehub, 1993a). That these effects occur before infants have knowledge of Western musical structure per se (Lynch, Eilers, Oller, & Urbano, 1990; Trainor & Trehub, 1992) suggests that the auditory system is designed to be able to process these intervals particularly well very early in development.

The octave interval (i.e., a 1:2 frequency ratio) is also perceptually privileged in both infancy and adulthood. Tones

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Correspondence concerning this article should be addressed to Laurel J. Trainor, Department of Psychology, McMaster University, Hamilton, Ontario, Canada L8S 4K1. Electronic mail may be sent via Internet to ljt@mcmaster.ca.

an octave apart sound similar to adults (e.g., see Schellenberg & Trehub, 1994b). Octave displacements of tones that interfere in a tonal memory task show a similar pattern of interference (e.g., Deutsch, 1973), and melodies distorted by octave displacements of notes are still recognizable (e.g., Idson & Massaro, 1978; Massaro, Kallman, & Kelly, 1980). Further, 3-month-old infants have been shown to dishabituate to (i.e., detect) changes in a melody of a major seventh (8:15) and minor ninth (15:32) but not to changes of an octave (Demany & Armand, 1984), indicating that octaves sound similar to these inexperienced listeners as well.

It has been known for a long time that pitch intervals with small-integer ratios are important in Western musical structure. Indeed, Western musical structure (as well as other musical structures) is based on the octave: Notes an octave apart are assigned the same note name. Further, the two most important notes of both the Western major and minor scales, the *tonic* and the *dominant,* are a perfect fifth apart. Melodies most often end on the tonic note, and harmony based on the dominant is unstable, requiring resolution to tonic harmony. Thus, models of musical pitch perception are typically multidimensional to capture both the similarity of pitches close in frequency as well as the similarity of pitches related by octave and perfect fifth intervals (e.g., Jones, 1990; Shepard, 1982). The usual explanation of the privileged perceptual status of the octave and perfect fifth intervals for Western adults involves experience with Western music (e.g., Dowling & Harwood, 1986; Krumhansl, 1990). Indeed, experienced individuals often show greater effects of ratio simplicity (e.g., Allen, 1967; Platt & Racine, 1987). However, perfect fifth and octave intervals also occur prominently across different musical systems (e.g., see Dowling & Harwood, 1986; Guernsey, 1928; Kolinski, 1967; Sachs, 1943). The cross-cultural prevalence of the perfect fifth and octave as well as infants' superior processing of these intervals suggest that there are intrinsic constraints on mechanisms of auditory pattern processing and that musical systems may have developed in such a way as to capitalize on the perceptual properties of these intervals.

A number of researchers have formalized the concept of ratio simplicity by proposing precise indexes (e.g., Levelt, van de Geer, & Plomp, 1966; Schellenberg & Trehub, 1994b; van de Geer, Levelt, & Plomp, 1962). On the basis of studies of melodic processing, Trehub and her colleagues (e.g., Schellenberg & Trehub, 1994b; Trainor & Trehub, 1993a, 1993b; Trehub & Trainor, 1993) have suggested that pitch intervals with small-integer frequency ratios may be intrinsically easy to process or learned very rapidly. In the experiments reported here, I tested infants' and adults' discrimination of semitone (i.e., one twelfth of an octave) changes to simultaneous octave and perfect fifth intervals in comparison to intervals similar in size (i.e., pitch distance) but whose component tones stand in much more complex frequency ratios.

The idea that small-integer frequency ratios are important in the perception of simultaneous tones can be traced as far back as Pythagoras. He is credited with discovering that vibrating strings whose lengths stand in smaller integer ratios result in simultaneous tones that sound more *consonant,* or pleasing, than do strings whose lengths stand in more complex ratios, which sound more *dissonant,* or displeasing. Since this time, the basis of consonance and dissonance has been examined by a number of scholars, notably Rameau (1722/1971), who proposed that tones standing in small-integer ratios sound consonant because they derive from the intervals formed by the harmonics of a single complex tone, and Helmholtz (1885/1954), who proposed that consonance is related to the number of harmonics in common between the component notes forming the interval. Tones standing in small-integer frequency ratios have more overtones in common than do tones standing in more complex relations. (Thus, according to this explanation, there should be no effects of frequency ratio with sine wave tones.)

Two kinds of consonance are thought to occur. *Tonal,* or *sensory, consonance* refers to the perception of consonance independent of musical experience (Plomp & Levelt, 1965). In this case, consonance for sine wave tones appears to be simply a function of the frequency separation of the tones. Tones within a critical band (roughly, a critical band corresponds to the width of the auditory filters) interact, resulting in the sensation of *beating* when very close in frequency and *roughness* when somewhat less close in frequency. Above 500 Hz the critical band is approximately one fourth of an octave; below 500 Hz it becomes somewhat larger. For combinations of complex tones—that is, tones containing harmonics—Plomp and Levelt proposed that the perception of dissonance occurred when noncoinciding harmonics between the two tones differed by less than a critical band. Such harmonics would interact in the same manner as the sine wave tones discussed above. The more harmonics occurring within critical bands, the more dissonant the interval (Kameoka & Kuriyagawa, 1969a, 1969b). Complex tones with simpler frequency ratios sound more consonant than those with more complex ratios because they have more coinciding harmonics and fewer noncoinciding harmonics within critical bands (Kameoka & Kuriyagawa, 1969a, 1969b). Thus, octave and perfect fifth intervals sound most consonant. However, in this view, it is not the small-integer relation that is important, per se, but rather the harmonic overlap, which can, in experimental settings, be manipulated separately from the frequency ratio of the fundamentals by creating sounds with certain harmonics missing (Kameoka & Kuriyagawa, 1969b) or with inharmonic (i.e., noninteger multiples of the fundamental) partials (Geary, 1980).

In musical consonance, however, the degree of perceived consonance is affected by the musical context, such that the same physical stimulus can be perceived by the same listener to be consonant in one context but dissonant in another (Cazden, 1980). Musical consonance is thought to be learned, because listeners from different cultures differ in their perception of whether a particular stimulus in a particular context is consonant or not (e.g., Butler & Daston, 1968; Dowling & Harwood, 1986). Terhardt (1974), following Rameau (1722/1971) proposed that the special role of octave and fifth intervals may derive from experience with the overtone structure of complex sounds, particularly vowels, that occur in the child's natural environment.

The hypothesis that simple ratio intervals are intrinsically easy to process or learned very early is related to the notion of consonance because small-integer frequency ratios are perceptually special in both. However, there are important differences. The former concerns discrimination performance, whereas consonance is concerned with aesthetic judgments. The discrimination enhancement for small-integer ratios appears to have little in common with musical consonance, as it is evident in infancy, before the acquisition of knowledge specific to the musical system of exposure. With respect to sensory consonance, frequency ratio simplicity is only indirectly important (but see the General Discussion section): In natural sounds, frequency ratio simplicity is correlated with the extent to which noncoinciding harmonics of the component tones fall within critical bands, which is the main determinant of the perception of dissonance. As sensory consonance is thought to arise largely from properties of the basilar membrane, it would be expected that sensitivity to sensory consonance should arise early in development. Indeed, Schellenberg and Trainor (1996) demonstrated that 7-month-olds and adults perceive sensory consonance similarly.

I examined the possibility of processing advantages for simultaneous intervals with small-integer ratios in the absence of sensory consonance. To accomplish this, I used intervals larger than a critical bandwidth and sine wave tones to eliminate sensory effects of interactions between harmonics. The relatively late development of sensitivity to implied harmony in music and the rarity of harmony across musical systems suggest that processing advantages for simultaneous small-integer ratios might occur somewhat later in development than do those for melodic small-integer ratios. Adults were compared with 6- to 8-month-olds, the youngest age for which melodic small-integer effects have been demonstrated. In particular, the octave was compared with the major seventh interval (one semitone smaller in pitch distance, with a ratio of 8:15), and the perfect fifth interval was compared with the tritone interval (one semitone smaller in pitch distance, with a ratio of 32:45). In each case, there were two conditions, one with the simple ratio interval as the standard stimulus and the complex ratio interval as the comparison stimulus, and the other with the standard and comparison stimuli reversed. Asymmetries in performance such that two stimuli are easier to discriminate when one is the standard than when the other is the standard are found when one stimulus is easier to process than the other (e.g., Bharucha & Krumhansl, 1983; Bharucha & Pryor, 1986; Krumhansl, 1979; Schellenberg & Trehub, 1994a; Trainor & Trehub, 1993a, 1993b). Thus I expected that performance would be superior when the octave or perfect fifth intervals were the standard stimulus than when they were the comparison or changed stimulus.

The mechanisms behind such asymmetries are not entirely clear. One possibility is that a standard stimulus sets up expectations or primes certain intervals through spreading activation; musically meaningful standards will cause more priming than will less musically meaningful standards, leading to superior discrimination. Because octave or perfect fifth intervals may define a musical key more clearly than tritone or major seventh intervals (Tekman & Bharucha, 1992; but see Butler, 1989; Butler & Brown, 1984), the overall context was controlled by transposing successive intervals in two ways, one involving transposition by perfect fifth and perfect fourth intervals and the other involving transposition by whole tone intervals (see the *Stimuli* section of Experiment 1). In any case, as infants do not yet have knowledge of key membership (Lynch et al., 1990; Trainor & Trehub, 1992), and asymmetry effects with melodic intervals occur in infancy (Cohen et al., 1987; Schellenberg & Trehub 1994a; Trainor & Trehub, 1993a, 1993b), it is unlikely that musical expectations can entirely account for these effects. A more plausible mechanism for asymmetry effects involves the notion that some intervals are difficult to encode and are assimilated to nearby intervals that are easier to process, but these intervals are processed as poor or out-of-tune instances of these nearby intervals. When a difficult-to-encode standard interval is followed by the actual interval to which it is assimilated, the second interval is perceived to be a good instance of the standard interval, and hence the discrimination is not made. When the standard interval is easy to encode, however, a change to a difficult-to-encode interval sounds like a poor or out-of-tune instance of the standard and is readily discriminated. In any case, the mechanisms underlying such asymmetries are not the focus of this article; rather, asymmetries in performance are used as a means for investigating whether infants demonstrate differential performance for simultaneous intervals based on ratio simplicity.

Infants' discrimination of changes to simultaneous intervals was tested with a go/no-go procedure involving a conditioned head-turn response. Adults were tested in a similar procedure but responded by raising their hand when they heard a change. Adults were tested in a within-subjects design; the same individuals completed both conditions involving the comparison of two intervals. Whereas this design is preferable to a between-subjects design in that it is more powerful, it proved to be too long for infants, so they were tested in a between-subjects design.

Experiment 1

Method

Participants. Eighty infants (37 girls, 43 boys) between 6 and 8 months of age ($M = 7.13$ months) participated in the eight conditions (10 per condition). All infants were born within 2 weeks of term, weighed at least 2,500 g at birth with no known abnormalities, and were healthy at the time of testing. A further 7 were excluded for failing to pass training (3) or failing to complete the test session because of fussing (4). Forty adults (28 women, 12 men) between 18 and 28 years of age ($M = 20$ years) participated. None was a professional musician; 33 had between 0–5 years of music lessons, and 7 had over 5 years of music lessons.

Apparatus. The stimuli were played by a Macintosh IIci computer, with an Audiomedia card to enable 16-bit sound generation, using custom-written software that interfaced with the public-domain Synthesize program. The output from the Audiomedia card was fed through a Denon amplifier (PMA-480R; Nippon

Columbia Company, Japan) to an audiological (i.e., very flat) loudspeaker (GSI) located in a sound-attenuating chamber (Industrial Acoustics Company, Bronx, NY). The loudspeaker was located to the participant's left. Under the loudspeaker was a box containing four chambers, each with its own lights and animated toy. The front of the box was smoked Plexiglas; reinforcing toys could only be seen when the lights in their chamber were turned on. The lights, toys, and a button box were connected to the computer by means of a custom-built interface box to a Strawberry Tree I/O card.

Stimuli. In each of eight conditions (see Table 1), participants were exposed to repetitions of two tones presented simultaneously and were required to detect when the higher of the tones was changed by one semitone (i.e., one twelfth of an octave using a log frequency scale). In half the conditions, successive repetitions were related by perfect fifth (2:3) or perfect fourth (3:4) intervals, and in the other half, by whole tone (i.e., two semitones) intervals. Successive repetitions were presented in a quasi-random transposition sequence, with the following restrictions. In the perfect transposition (P) conditions, the lower tone of each repetition was 1 of 233, 349, 262, 392, 294, 440 Hz (B-flat$_3$, F$_4$, C$_4$, G$_4$, D$_4$, A$_4$), such that the lower tones of adjacent repetitions were adjacent on this list. In the whole tone (WT) conditions, the lower tones of adjacent repetitions were adjacent on the following list: 262, 294, 330, 370, 415, 466 Hz (C$_4$, D$_4$, E$_4$, F#$_4$, G#$_4$, A#$_4$).

There were two different conditions involving the perfect fifth interval (component tones standing in a 2:3 frequency ratio), each presented with each of the transposition types, for a total of four conditions. In one condition, the standard repeated interval was a perfect fifth (P5), and the to-be-detected or changed interval was a tritone (TT; i.e., the top note was lowered by a semitone, forming a 32:45 ratio). This condition was called P5-TT. In the other condition (TT-P5), the standard and changed intervals were reversed. Adults completed both stimulus orders within a particular transposition type, half receiving P5-TT first and half TT-P5 first.

Similarly, there were two different conditions involving the octave interval (1:2), and again each was presented with each of the transposition types. In one condition, the standard repeated interval was an octave (P8) and the changed interval was a major seventh (M7; i.e., the top note was lowered by a semitone, forming an 8:15 ratio); this was the P8-M7 condition. In the other condition (M7-P8), the standard and changed intervals were reversed. Again, adults completed both stimulus orders within a particular transposition type, half receiving P8-M7 first and half receiving M7-P8 first.

In training (see the *Procedure* section that follows), the changed interval was always a minor second (15:16 ratio), which represented a large pitch change to the upper note in each condition (5, 6, 10, and 11 semitones for conditions TT-P5, P5-TT, M7-P8, and P8-M7, respectively).

Each interval was presented in a pattern of two 200-ms repetitions of the interval, separated by a 200-ms silence to maximize attention (see Figure 1). Each pattern was separated by 1,000 ms. In each condition, participants listened to a repeating background of transpositions of the standard interval pattern. Every so often a trial was presented (see *Procedure* section). On change trials, the two repetitions of the standard interval forming the pattern were replaced by the changed interval, such that the lower tone was at the same pitch level as the standard interval it was replacing. On control trials, the standard pattern was presented; to the listener, control trials were indistinguishable from the repeating background. Intervals were presented at approximately 60 dB (A), and background noise was 23 dB (A) as measured by a Bruel and Kjaer Integrating Sound Level Meter (Type 2231). Spectral analyses (using the Kyma system with 10-Hz sampling bins) revealed that energy at the sine wave components forming each interval was at least 35-dB higher than the energy at any other frequency, measured at the location of the participant's head.

Procedure. A go/no-go procedure was used (e.g., see Trainor & Trehub, 1993a, 1993b). Participants sat in the sound-attenuating chamber (infants on their parents' laps) facing the experimenter, who sat behind a small table to hide the button box. Parents and the experimenter listened to music through headphones to mask what the participant was hearing. The background of transpositions of the standard interval pattern played continuously (see the *Stimuli* section above). When the participant was attentive and facing the experimenter, he or she signaled to the computer via the button box (which was out of sight) to initiate a trial. Thus there was a variable number of repetitions (a minimum of two) of the standard interval between trials. Half of the trials were change trials, in which the standard interval was replaced with the changed interval; the other half were control trials, in which the standard interval was presented as in the background. Infants were trained (see below) to turn their head at least 45° from midline toward the loudspeaker whenever they heard a change in the stimuli. Adults were instructed to raise their hand whenever they heard a change. In both cases, the experimenter relayed these responses to the computer by means of the button box. If there was a response within 3.5 s of the beginning of a change trial, the computer automatically initiated reinforcement, consisting of a 4-s activation of one of the four toys and associated light located under the loudspeaker. (These toys appeared to reinforce adults as well as infants; at the very least they provided feedback.) Responses on control trials and during the background presentations were not reinforced. Change and control trials were presented in a quasi-random order, with the restriction of no more than 2 consecutive control trials. In all, there were 30 trials (15 change and 15 control).

Prior to the test phase there was a training phase that differed from the experimental phase in that the changed interval was much larger and easier to detect (see the *Stimuli* section). The purpose of the training in the infant procedure was to teach infants to turn toward the speaker to respond. Infants typically localize (turn to) a

Table 1
Summary of the Stimuli in Each Condition

Experiment & condition	Transposition	Ratio: Standard	Ratio: Change	Ratio: Training
Experiment 1				
P5-TT	Perfect	2:3	32:45	15:16
P5-TT	Whole tone	2:3	32:45	15:16
TT-P5	Perfect	32:45	2:3	15:16
TT-P5	Whole tone	32:45	2:3	15:16
P8-M7	Perfect	1:2	8:15	15:16
P8-M7	Whole tone	1:2	8:15	15:16
M7-P8	Perfect	8:15	1:2	15:16
M7-P8	Whole tone	8:15	1:2	15:16
Experiment 2				
P5-m6	Perfect	2:3	5:8	15:16
m6-P5	Perfect	5:8	2:3	15:16
P8-m9	Perfect	1:2	15:32	15:16
m9-P8	Perfect	15:32	1:2	15:16
Experiment 3				
P8-M7	Perfect	1:2	8:15	5:6
M7-P8	Perfect	8:15	1:2	5:6
P8-M7	Perfect	1:2	8:15	8:15
M7-P8	Perfect	8:15	1:2	1:2

Note. P5 = perfect fifth; TT = tritone; P8 = octave; M7 = major seventh; m6 = minor sixth; m9 = minor ninth.

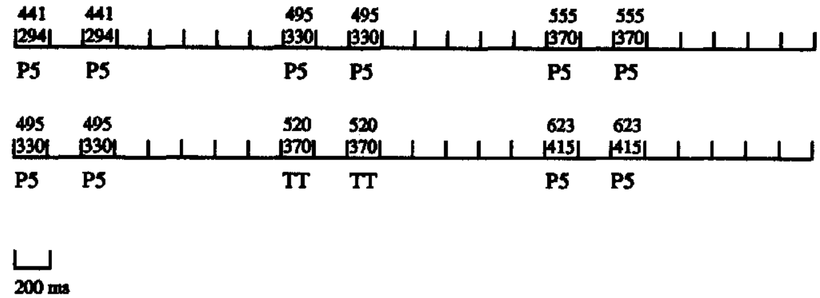

Figure 1. Example stimuli from the perfect fifth–tritone (P5-TT) condition, showing six successive repetitions of the pattern. The numbers above the line indicate the frequencies of the tones presented; the symbols under the line indicate the type of interval. Note that in the fifth repetition, a change trial, the upper frequency is lowered one semitone to form a TT interval.

novel sound; thus the training was designed to strengthen this natural response with reinforcement. For adults, the training provided familiarization with the stimuli and procedure. Four consecutive correct responses within 20 change trials were required in order to proceed to the test phase.

There were eight different conditions—P5-TT, TT-P5, P8-M7, M7-P8 (where the first abbreviation represents the standard interval and the second the changed interval)—crossed with transposition types (P and WT). Adults were tested in a partial within-subjects design: Each adult completed two conditions (either P5-TT and TT-P5 or P8-M7 and M7-P8) with the same transposition type (either P or WT). Half the adults in each group completed one condition first, and half completed the other condition first. Training was given before each condition. Infants were tested in a between-subjects design, as they were not able to maintain their attention through two conditions. It was expected that conditions with perfect intervals as the standard stimulus (i.e., P5-TT, P8-M7) would be easier than conditions with a complex interval as standard (i.e., TT-P5, M7-P8).

Results and Discussion

The proportion of responses on change trials (hits) and control trials (false alarms) was transformed to d' scores using the yes–no signal detection tables (Elliott, 1964) for each participant in each condition. To deal with proportions of zero or one, which lead to infinite d' scores and are assumed to reflect sampling error because of the limited number of trials obtained from each participant (see Macmillan & Kaplan, 1985), proportions were calculated by adding .5 to the number of responses and dividing by the number of trials of that type plus 1 (i.e., 16). This adjustment has little effect on d' scores and maintains the original ranking of scores (see Thorpe, Trehub, Morrongiello, & Bull, 1988). Chance performance has an expected d' value of zero, and the maximum achievable under these conditions is 3.76. Infants' performance (Figure 2, top graph) was above chance levels in the two conditions with simple ratio standard intervals: $t(19) = 10.18, p < .0001$, and $t(19) = 9.25, p < .0001$, for P5-TT and P8-M7, respectively. Infants' performance was also above chance levels in one of the two conditions with complex ratio standard intervals: $t(19) = 2.65, p < .008$, and $t(19) = 1.49, p < .08$, for TT-P5 and M7-P8, respectively. Adults' performance (Figure 2, bottom graph) was above chance in all conditions (all $ps < .0001$).

The performance of infants and adults was evaluated with separate analyses of variance (ANOVAs) because adults were tested in a partial within-subjects design, and infants were tested in a between-subjects design. Other differences between the procedures (notably, adults received verbal

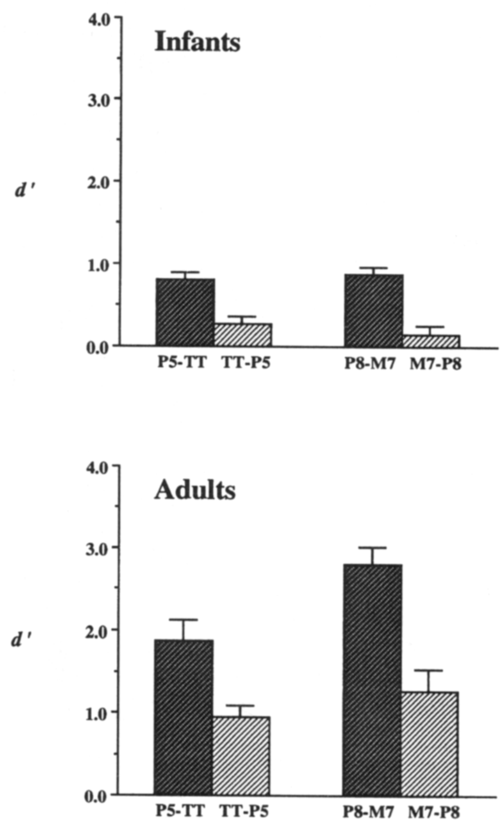

Figure 2. The mean (and standard error) d' performance of infants and adults tested in the perfect fifth–tritone (P5-TT), tritone–perfect fifth (TT-P5), octave–major seventh (P8-M7), and major seventh–octave (M7-P8) conditions in Experiment 1.

instructions, whereas infants obviously did not) render direct comparisons between performance levels of infants and adults suspect. Rather, a comparison of the pattern of the performance of infants and adults across the various conditions is most informative.

An ANOVA was performed on the infants' data, with standard interval simplicity (simple [i.e., P5-TT and P8-M7] vs. complex [i.e., TT-P5 and M7-P8]), P5ths–P8ths (fifths [i.e., P5-TT and TT-P5] vs. eighths [i.e., P8-M7 and M7-P8]), and transposition type (P vs. WT) as variables. The only significant effect was of standard interval simplicity, $F(1, 72) = 45.39$, $p < .0001$ (see Figure 2, top graph). Performance was better when the simple ratio perfect intervals were the standard than when the complex intervals were the standard (i.e., conditions P5-TT and P8-M7 were superior to TT-P5 and M7-P8), as predicted.

Adults' performance was evaluated in an ANOVA with standard interval simplicity as a within-subjects variable and P5ths–P8ths, transposition type, and condition order (simple standard first [i.e., P5-TT and P8-M7 first] vs. complex standard first [i.e., TT-P5 and M7-P8 first]) as between-subjects variables. As for infants, there was a significant effect of standard interval simplicity, $F(1, 32) = 43.0$, $p < .0001$. Performance was much better when the simple ratio perfect intervals were the standard than when the complex ratio intervals were the standard (i.e., conditions P5-TT and P8-M7 were superior to TT-P5 and M7-P8, respectively), as predicted (see Figure 2, bottom graph). There was also an effect of P5ths–P8ths, $F(1, 32) = 6.19$, $p < .022$, indicating that performance was better on conditions involving octaves (P8) than on conditions involving perfect fifths (P5). This is also in line with the framework I presented earlier in this article, as the octave (1:2) is even simpler in frequency ratio than the perfect fifth (2:3). The only other significant effect was a condition order × standard interval simplicity interaction, $F(1, 32) = 5.22$, $p < .03$. Performance on the conditions with simple standard interval simplicity (i.e., P5-TT and P8-M7) was higher if heard first than second, whereas performance on the conditions with complex standard interval simplicity (i.e., TT-P5 and M7-P8) was lower if heard first than second. Normally, performance would be expected to improve with practice; this is consistent with the finding of better performance on the complex standard interval conditions when heard second rather than when heard first. A speculative explanation of the interaction, then, is that exposure to the complex standard (i.e., conditions TT-P5 and M7-P8) led to such processing difficulties that even "normal" processing of simple intervals became impaired, either through confusion or fatigue. Interestingly, there was no effect of, or interactions involving, transposition type, suggesting that musical context was not playing a role in these effects.

The correlation between number of years of music lessons and the difference in d' scores between the simple standard and the complex standard pairs was low and nonsignificant ($r = .08$, $N = 20$). However, as the range of musical training among the participants was not particularly great, this lack of significant correlation should not be overinterpreted.

These results indicate that infants and adults show very similar effects, with enhanced discrimination of changes to simultaneous intervals whose sine wave component tones are related by 1:2 or 2:3 frequency ratios compared with intervals having more complex ratios of 32:45 and 8:15. Unlike adults, infants did not show the further effect of higher performance on octave over perfect fifth conditions; however, this is not surprising because the effect was subtle in adults, and infants' performance is generally much lower and more variable than that of adults; in addition, the infants were tested with a less powerful experimental design than were the adults. Thus, these results provide evidence that simultaneous intervals with simple ratios are easier to process early in life than are intervals with more complex ratios.

One possible problem with this interpretation is that the easier conditions all involved detecting a change from a larger to a smaller interval, whereas the more difficult conditions involved detecting a change from a smaller to a larger interval. It is possible that regardless of interval simplicity, it is easier to detect changes in the former case than in the latter. Experiment 2 was designed to separate effects of ratio simplicity and the direction of the change in interval size. Infants and adults were tested on their ability to discriminate octave and minor ninth intervals, as well as perfect fifth and minor sixth intervals. The minor ninth interval is one semitone larger than the octave interval and has a relatively complex ratio (15:32) between its component tones; the minor sixth interval is one semitone larger than the perfect fifth interval and has a somewhat more complex ratio (5:8). Thus, in Experiment 2, the conditions expected to be easier involved detecting changes from smaller to larger intervals, whereas the conditions expected to be harder involved detecting changes from larger to smaller intervals.

Experiment 2

Method

Participants. Forty infants (24 girls, 16 boys) similar to those described in Experiment 1 (mean age = 7.07 months) participated in the four conditions (10 per condition). One further infant was excluded for failing to pass training. Twenty-eight adults (21 women, 7 men) between 17 and 41 years of age ($M = 21$ years) completed both conditions. None was a professional musician; 24 had between 0–5 years of music lessons, and 4 had over 5 years of music lessons.

Apparatus and stimuli. The apparatus and stimuli were identical to those of Experiment 1 in all respects except the following (see Table 1). In all conditions, successive repetitions were related by perfect fifth or perfect fourth intervals as in the P condition in Experiment 1. There were two different conditions involving the perfect fifth interval: One condition, in which the standard interval was a perfect fifth and the changed interval a minor sixth (m6; ratio 5:8), was called P5-m6; the other condition, in which the standard and changed intervals were reversed, was called m6-P5. Similarly, there were two different conditions involving the octave interval: P8-m9, in which the standard interval was an octave and the changed interval a minor ninth (ratio 15:32); and m9-P8, in which the standard and changed intervals were reversed.

Procedure. Within each condition the procedure was identical to that of Experiment 1. Adults were tested in a partial between-subjects design: Fourteen adults completed both P5-m6 and m6-P5, and 14 completed both P8-m9 and m9-P8 (in each case half received one condition first, and half received the other condition first). As infants were not able to complete two sessions, they were tested in a between-subjects design, with each group of 10 infants completing one of the P5-m6, m6-P5, P8-m9, and m9-P8 conditions.

Results and Discussion

Individual scores were transformed to d' scores as in Experiment 1. Infants' performance (Figure 3, top graph) was above chance levels in the two conditions with simple ratio standard intervals: $t(9) = 2.47$, $p < .02$, and $t(9) = 12.28$, $p < .0001$, for P5-m6 and P8-m9, respectively. Infants' performance was also above chance levels in one of the two conditions with complex ratio standard intervals: $t(9) = .44$, $p > .33$, and $t(9) = 2.62$, $p < .014$, for m6-P5 and m9-P8, respectively. Adults' performance (Figure 3, bottom graph) was above chance in all conditions (all $ps < .0002$).

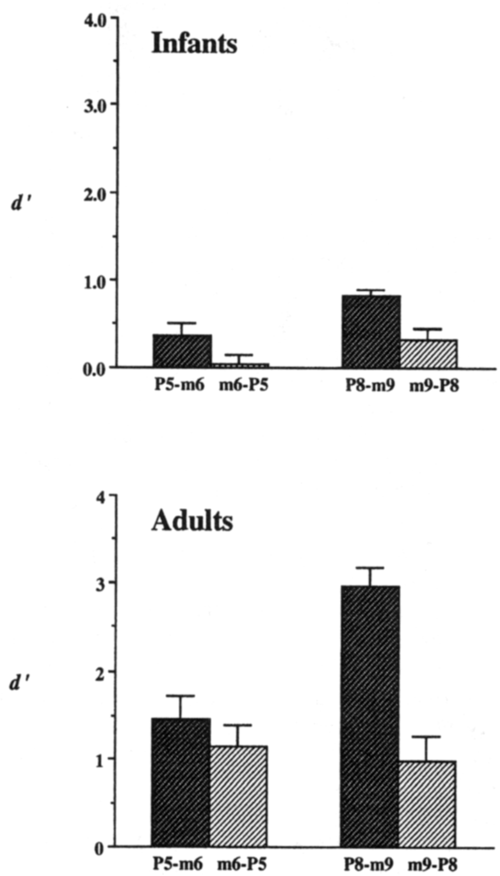

Figure 3. The mean (and standard error) d' performance of infants and adults tested in the perfect fifth–minor sixth (P5-m6), minor sixth–perfect fifth (m6-P5), octave–minor ninth (P8-m9), and minor ninth–octave (m9-P8) conditions in Experiment 2.

The infants' and adults' data were again analyzed separately because of the different experimental designs. The infants' data were analyzed in an ANOVA, with standard interval simplicity (simple [i.e., P5-m6 and P8-m9] vs. complex [i.e., m6-P5 and m9-P8]) and P5ths–P8ths (fifths [i.e., P5-m6 and m6-P5] vs. eighths [i.e., P8-m9 and m9-P8]) as variables. The effect of standard interval simplicity was significant, $F(1, 36) = 13.8$, $p < .001$, with better performance when the simple ratio perfect intervals were the standard than when the complex ratio intervals were the standard, as predicted (see Figure 3, top graph).

There was also a significant effect of P5ths–P8ths, $F(1, 36) = 11.6$, $p < .002$, indicating that performance was overall superior on the conditions involving the octave over those involving the perfect fifth, as would be expected because the octave has a simpler ratio (1:2) than the perfect fifth (2:3). However, the comparable difference between octave and perfect fifth conditions in Experiment 1 was not significant. As can be seen by comparing Figures 1 and 2 (top graphs), this difference across Experiments appears to involve depressed performance on P5-m6 in comparison with P5-TT, and statistics showed this to be the case, $t(28) = 3.02$, $p < .005$. This is not surprising, however, when the difference between the complexity of the tritone (TT: 32:45) and minor sixth (m6: 5:8) intervals are considered. With simple standard intervals, then, the more complex are the changed intervals, the easier is the discrimination.

The adults' data were analyzed in an ANOVA, with standard interval simplicity as a within-subjects factor variable and P5ths–P8ths and condition order as between-subjects variables. As with the infants, there was a significant effect of standard interval simplicity, $F(1, 24) = 19.9$, $p < .0002$, with superior performance when the standard interval was the octave or the perfect fifth, as predicted (see Figure 3, bottom graph). There was an effect of P5ths–P8ths as well, $F(1, 24) = 6.8$, $p < .02$, with superior performance on conditions involving the octave over conditions involving the perfect fifth, paralleling the results of Experiment 1. Again, this is not surprising, as the ratio of the octave (1:2) is simpler than that of the perfect fifth (2:3). Additionally, there was a standard interval simplicity × P5ths–P8ths interaction, $F(1, 24) = 10.5$, $p < .003$, reflecting that there was a greater difference between performance on conditions P8-m9 and m9-P8 than between conditions P5-m6 and m6-P5. This interaction is also not surprising because the difference in simplicity between the ratios of the intervals involved in the former (1:2 and 15:32) is much greater than the difference in simplicity between the intervals involved in the latter (2:3 and 5:8). The correlation between number of years of music lessons and difference between d' scores across the simple standard and the complex standard pairs was low and nonsignificant ($r = .02$, $N = 28$).

Experiment 2 confirms that the direction of interval change is not mediating the effects of interval ratio simplicity for either infants or adults. It also provides additional evidence that for both infants and adults, discrimination of an interval change is easier when the standard interval has a simpler ratio than does the comparison interval. However, all conditions of both Experiments 1 and 2 included a training phase in which the comparison interval was always complex.[1] Thus, a third experiment was performed to examine the effects of two types of training. In the octave-displacement training condition, the interval to be detected was the same in the training and the test phases but was displaced upward by an octave in training so as to be in a different frequency range than the standard intervals. In the minor third training, the comparison interval in training was intermediate in complexity between the standard and comparison intervals in the test phase. Specifically, the minor third has a ratio of 5:6 and is referred to as an imperfect consonance.

Experiment 3

Method

Participants. Forty infants (20 girls, 20 boys) similar to those described in Experiment 1 (mean age = 7.06 months) participated in the four conditions (10 per condition). Two other infants were excluded for failing to pass training. Sixteen adults (12 women, 4 men) between 18 and 22 years of age (M = 20 years) completed both conditions. None was a professional musician; 11 had between 0–5 years of music lessons, and 5 had over 5 years of music lessons.

Apparatus and stimuli. The apparatus and stimuli were identical to those of Experiment 1 in all respects except the following (see Table 1). In all four conditions, successive repetitions were related by perfect fifth or perfect fourth intervals as in the P condition of Experiment 1. In two conditions, the test phase was identical to that of P8-M7 in Experiment 1, and in the other two conditions it was identical to that of M7-P8 in Experiment 1. Crossed with this variable of standard interval simplicity was training type. In two conditions (minor third training), the interval to be detected during the training phase was a minor third (5:6 ratio), which represented a change of eight or nine semitones for the P8-M7 and M7-P8 conditions, respectively. In the other two conditions (octave-displaced training), the interval to be detected was the same as during the following test phase but was transposed out of range by an octave.

Procedure. Within each condition, the procedure was identical to that of Experiment 1. Adults were tested in a partial between-subjects design: Eight adults had minor third training (half completed P8-M7 first, and half completed M7-P8 first); 8 had octave-displaced training (again, half completed P8-M7 first, and half completed M7-P8 first). Infants were tested in a between-subjects design, with each group of 10 infants participating in one of the P8-M7 and M7-P8 conditions, with one kind of training (minor third or octave displaced).

Results and Discussion

Individual scores were transformed to d' scores as in Experiment 1. Again the infants' and adults' data were analyzed separately because of the different experimental designs. Infants' and adults' performances (Figure 4) were above chance levels in all conditions (all $ps < .02$ for infants; all $ps < .003$ for adults).

The infants' data were analyzed in an ANOVA, with standard interval simplicity (i.e., P8-M7 vs. M7-P8) and training type (minor third vs. octave displaced) as variables. Only standard interval simplicity was significant, $F(1, 36) = 4.82$, $p < .035$, with better performance on P8-M7 than on M7-P8, as predicted (see Figure 4, top graph). There was no effect of, or interaction involving, training type. Further, when an ANOVA was conducted combining the data of Experiment 3 with those of the P8-M7 and M7-P8 (related keys transposition) conditions from Experiment 1, with standard interval simplicity (i.e., P8-M7 vs. M7-P8) and training type (minor second [Experiment 1] vs. minor third vs. octave displaced) as variables, only standard interval simplicity was significant, $F(1, 54) = 18.14$, $p < .0001$. Again there was no effect of, or interaction involving, training type.

The adults' data were analyzed in an ANOVA, with standard interval simplicity (P8-M7 vs. M7-P8) as a within-subjects variable and condition order (P8-M7 first vs. M7-P8 first) and training type (minor third vs. octave displaced) as

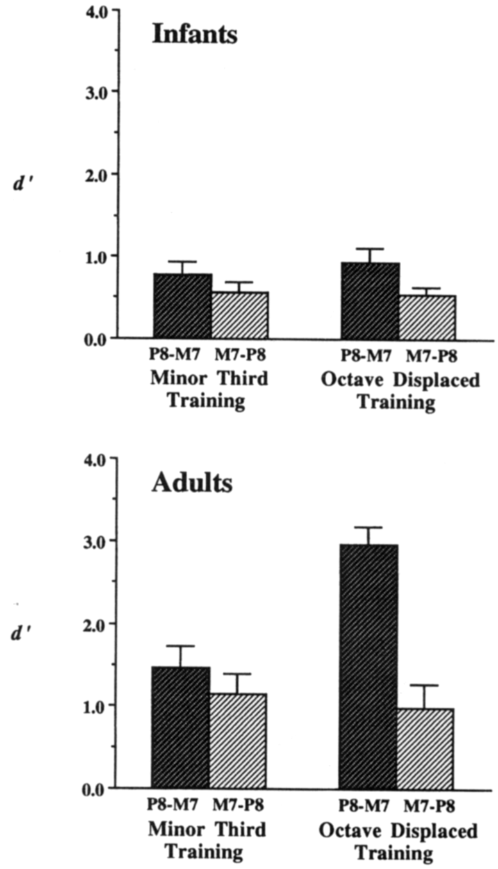

Figure 4. The mean (and standard error) d' performance of infants and adults tested in the octave–major seventh (P8-M7) and major seventh–octave (M7-P8) conditions across minor third and octave-displaced training types in Experiment 3.

[1] As pointed out by reviewers of a draft of this article, it is possible that listeners were trained to respond only to complex intervals.

between-subjects variables. The only significant effect was of standard interval simplicity, $F(1, 12) = 24.40, p < .0003$, with better performance on P8-M7 than on M7-P8, as expected. When the P8-M7 and M7-P8 conditions from Experiment 1 (with minor second training type) were included in the analysis, the only significant effect remained that of standard interval simplicity, $F(1, 23) = 51.72, p < .0001$. Although it appears in Figure 4 (bottom graph) that there is a trend toward a greater difference between the P8-M7 and M7-P8 conditions with major third than with octave-displaced training for adults, training type and interactions involving training type did not reach significance. In fact, it made no significant difference whether the interval to be detected in training had a relatively complex ratio (minor second, Experiment 1), a ratio intermediate in complexity (minor third, Experiment 3), or the identical ratio to that presented in the test phase (octave displaced, Experiment 3). The important finding was that there was a strong effect of standard interval simplicity across all types of training.

In line with the previous two Experiments, the correlation between number of years of music lessons and difference between d' scores in the P8-M7 and M7-P8 conditions was low and nonsignificant ($r = .066, N = 16$).

As discussed earlier, Schellenberg and Trehub (1994b) devised an index of ratio simplicity consisting of the reciprocal of the natural logarithm of the sum of the two integers forming the ratio, when the ratio is in its simplest form. The results of Experiments 1, 2, and 3 provide data to further test the generality of this index. For adults, the correlation between the difference in d' performance for each participant on the pair of conditions they completed (in each case involving the same two intervals, e.g., P5-TT and TT-P5) and the difference between the indexes of ratio simplicity for the two intervals involved in each case (e.g., P5 and TT) was highly significant ($N = 84$, $r = .38$, $p < .0004$), suggesting that adults' performance depends on the degree of difference in ratio simplicity between the standard interval and the changed interval.

Infants were tested in a between-subjects design. The correlation between d' performance and the difference between the ratio simplicity index for the standard interval and the changed interval was highly significant ($N = 160$, $r = .50$, $p < .0001$). It was also possible to examine the effects of the standard and changed intervals separately. The indexes of ratio simplicity for both the standard and changed intervals were separately correlated with d' performance ($N = 160$, $r = .51$, $p < .0001$, and $N = 160$, $r = -.44$, $p < .0001$, respectively). Thus, infants' performance also depends on the degree of difference in ratio simplicity between the standard and the changed intervals.

General Discussion

These experiments indicate that it is easier for both infants and adults to discriminate changes to simultaneous perfect fifth and octave intervals with simple ratios of 1:2 and 2:3, respectively, between their component tones than to similar-sized intervals with more complex ratios. Thus, by 6 months of age, enhanced processing effects for simple ratios are evident with both melodic (sequential) and harmonic (simultaneous) intervals. The possibility, discussed earlier, that these effects might develop very late for simultaneous intervals has been ruled out. However, by 6 months of age, infants have had considerable listening experience, and there is evidence that vowel perception has begun to differentiate depending on the language of input (Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Polka & Werker, 1994). As no data are available on infants younger than 6 months, it is still possible that ratio simplicity effects might develop somewhat earlier for sequential than for simultaneous intervals.

The effects of small-integer frequency ratios are likely independent of the musical system of exposure. First, 6- to 8-month-olds do not appear to have knowledge of Western scale structure (Lynch et al., 1990; Trainor & Trehub, 1992) but show marked effects of small-integer frequency ratios on discrimination tasks. Second, with respect to learning, the sequential pitch structure of Western music appears to be learned more rapidly than does the simultaneous pitch structure (Trainor & Trehub, 1994), but there is no evidence that effects of small-integer frequency ratios with simultaneous intervals occur later in development than those with sequential intervals. Terhardt (1974) has suggested that the special status of simple frequency ratios may arise through exposure to the vowel sounds of the speech in the infants' natural environment, as the first two harmonics of such periodic sounds are separated by an octave, and the second and third harmonics, by a perfect fifth. It remains to be clarified how experience with the intervals between harmonics that fuse into a single percept affects the processing of intervals between the pitches of two different sounds (whether sequential or simultaneous). Even if experience with simple ratios is necessary for these effects, learning appears to be very rapid in this domain, suggesting that it may be "innately guided" (Gould & Marler, 1987; Jusczyk & Bertoncini, 1988). Innate guidance in this context refers to a predisposition of the organism to attend to certain stimuli, or features of stimuli, and rapidly learn to process them efficiently.

Sine wave tones were used in this study to eliminate the effects of interactions between harmonics. However, the possible influence of difference tones should also be considered before concluding that the results are independent of peripheral auditory effects. The difference tone most likely to be audible that arises from pairs of tones separated by a perfect fifth interval is one octave below the lower tone of the pair (see Plomp, 1965; Roederer, 1973). For octave intervals, the most audible difference tone is coincident with the lower tone. Difference tones arising from the major seventh, minor ninth, tritone, and minor sixth intervals, however, are not related by simple frequency ratios to either tone in the interval. Thus, it is possible that difference tones played a role in the differential discrimination found. However, the difference tones of the simple versus the complex ratio intervals differ in ratio simplicity, so a possible role of difference tones in these effects in no way diminishes the conclusion that intervals with small-integer ratios are easier to process. In any case, the stimuli were not presented at high intensity levels, so difference tones would have been very weak in comparison to the presented tones and would therefore be expected to have a minimal effect on performance.

Schellenberg and Trehub (1994b) have recently related three tasks that appear to be affected by relative simplicity of frequency ratios: judgments of consonance, judgments of similarity, and melodic interval discrimination performance. However, as noted earlier, there are some differences between the discrimination tasks and the judgment tasks. Notably, the effects of ratio simplicity on performance in the discrimination tasks are strong, even with sine wave tones or melodic presentation (i.e., in the absence of sensory consonance or dissonance), and the effects are thought to result directly from the processing mechanisms: Intervals with small-integer ratios are easier to encode, remember, and compare. However, the effects of ratio simplicity on judgments of consonance appear to be weak or absent when sine wave tones are used and to depend on musical experience. The more robust results with complex tones appear to be mediated primarily by relatively peripheral within-critical-band interactions between harmonics.

In this light, it is of interest to review the conditions under which small-integer ratio effects have and have not been found for sequential intervals as well as simultaneous intervals with sine wave component tones. With sequential intervals, similarity ratings rather than consonance ratings are generally reported. Ratings of the similarity of the tones composing a sequential interval have generally resulted in very small increases in the rated similarity of tones an octave apart, with an effect often only apparent in the data from musically trained individuals (Allen, 1967; Kallman, 1982; Thurlow & Erchul, 1977). In part, the weakness of these effects can be explained by the stimuli (see Schellenberg & Trehub, 1994b). For example, as Allen (1967) used intervals of four octaves, effects of this extremely large pitch range may have obscured effects of the octave relation. However, these data overall indicate weak, if any, effects of octave similarity judgments with individuals who are musically untrained. However, Krumhansl (1990, pp. 123–137) found a robust tendency for participants to rate tones separated by perfect fifths as more similar than tones separated by other intervals when the intervals were presented after a strong musical context was established, either by playing a scale or a cadence in a particular key.

Tasks involving discrimination of sequential intervals have shown more consistent results. Both infants and adults find it much easier to discriminate changes to melodies with prominent perfect fifth intervals than to melodies without perfect fifth intervals (Cohen et al., 1987; Trainor & Trehub, 1993a, 1993b). Schellenberg and Trehub (1994a) tested adults' discrimination of several melodic intervals with varying degrees of ratio simplicity. The interval was played 2½ times in a melodic sequence (i.e., lower, higher, lower, higher, lower tone). They found that changes from patterns with simpler frequency ratios to patterns with more complex frequency ratios were easier to detect than the reverse discriminations. Divenyi and Hirsh (1974) found higher identification of the temporal order of three-tone sequences when the tones were related by smaller integer ratios than by more complex ratios. Deutsch (1973) showed that octave displacements of tones that interfere in a tonal memory task show a similar pattern of interference. Interestingly, all of these discrimination tasks, and the one similarity judgment task that obtained a strong effect of ratio simplicity, involved embedding the interval of interest in a melodic context.

As for simultaneous intervals, consonance ratings for sine wave tone intervals generally reveal little or no effect of ratio simplicity (Plomp & Levelt, 1965). However, Kameoka and Kuriyagawa (1969a) found small increases in consonance ratings at octaves (1:2, 1:3, and 1:4 ratios) even when stimuli were presented at 47dB (SPL) to eliminate the effects of aural harmonics. In addition, Ayres, Aeschback, and Walker (1980, Experiment 3) found increases in consonance ratings at small-integer ratios with sine wave stimuli. Using a triadic comparison method in which participants rated the relative similarity of different intervals, Levelt et al. (1966) found that multidimensional scaling led to three dimensions, two related to frequency distance rather than ratio. The third dimension had no straightforward interpretation. However, local maxima and minima tended to occur at simple frequency ratios, indicating that simple ratios probably affected judgments, but, paradoxically, perfect fifths and octaves were maximally dissimilar to each other, the former occurring at a maxima and the latter at a minima. Thus, it appears that there are effects of ratio simplicity on consonance ratings for sine wave tones, but they are not strong effects. However, the discrimination data presented here revealed strong effects of ratio for simultaneous sine wave tones for both infants and adults. Again, though, the intervals in this discrimination task were embedded in a sequential pattern.

From this review, it is not clear whether discrimination is simply a more robust method for measuring the effects of ratio simplicity in comparison to similarity or consonance judgments, whether judgments of consonance and similarity tap different processing mechanisms than do discrimination judgments, or whether melodic processing is required for strong ratio simplicity effects to emerge. The latter notion is intriguing in light of recent studies indicating that simple pitch intervals and melodic sequences may be processed in different parts of the brain (Peretz, 1993; Zatorre & Halpern, 1993). Peretz (1993) presented the case of a patient with sequelar bilateral lesions, one in the left temporal lobe and one in the right fronto-opercular region, who had good pitch interval discrimination and good temporal pattern discrimination but who could not recognize formerly familiar melodies. Similarly, Zatorre and Halpern found that a group of patients with right temporal lobe excisions (for control of epilepsy) performed normally when discriminating which of two tones was higher in isolation but more poorly than "normal" participants and those with left temporal lobe excisions when distinguishing which of two pitches was higher when the pitches were embedded in a familiar melody.

Infants also show the enhanced effects of simple ratios in melodic contexts. If a melodic-processing module must be activated for this to occur, the implication is that this processing module is functioning in infants before they acquire specific knowledge about the particular musical system to which they are exposed. The early functioning of melodic processing (beyond simple interval processing) is of interest given the wealth of data describing infants' early sensitivity to the prosodic features of speech (e.g., Fernald, 1992; Papousek, Bornstein, Nuzzo, Papousek, & Symmes, 1990). In both the music and speech domains, infants appear predisposed to attend to the pitch patterns as they unfold in time (Fernald & Kuhl, 1987; Trehub & Trainor, 1990; Trehub, Trainor, & Unyk, 1993).

It can be concluded that it is much easier for both infants and adults to discriminate changes to octave and perfect fifth intervals than to intervals whose component tones stand in more complex ratios. The idea that common processing mechanisms might underlie ratio simplicity effects on judgments of similarity, judgments of consonance, as well as pitch interval discrimination is intriguing. However, discrepancies both at the theoretical level as well as across experimental data suggest that more research is needed to clarify the role of small-integer frequency ratios in these different tasks. The results across studies are consistent with the notion that at least some effects of small-integer frequency ratios may occur specifically at the level of melodic processing rather than at the levels of peripheral or pitch interval processing. Thus, judgments of consonance for isolated intervals comprising complex tones may primarily tap the effects of simple ratios at relatively peripheral levels, whereas the discrimination of melodic sequences may tap the effects of simple ratios at a more central stage of processing.

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