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Development of Tonality Induction: Plasticity, Exposure, and Training

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Tonality induction is the natural outcome of acoustic redundancies in music and the predisposition of the brain to represent these redundancies. In the simplest case, tonality induction relies on frequency resolution and a memory accumulator. A review of the literature suggests that these and other more sophisticated building blocks (analysis of complex tones and sensitivity to sequential characteristics of musical patterns) are in place to contribute to tonality induction in the first year of life. As further revealed by life-span studies of preference and recognition for stylistically different popular music excerpts, two other constraints must also be considered: (1) brain plasticity and (2) degree of exposure to music of particular styles. The importance of a final factor, (3) formal music performance training, is shown in studies of (a) the benefits of the major triad frequency ratio relations (4:5:6) on memory (absolute judgment) for tones in an unfamiliar context (b) the applicability of a model based on a key-finding algorithm to pitch memory in a tonal context, and (c) the probe-tone task.

> We now know that just being exposed to a language is not enough for learning it. Something is needed to make language worth acquiring, whatever its syntax.
>
> Bruner, 1983, p. 168

TONALITY induction is a mental process that, at the very least, results in a listener's expectations about the pitch alphabet in an unfolding piece of music. The phenomenal evidence for this set of expectations is an implicit context against which encoded musical sounds are evaluated. It is this context, known as the tonal hierarchy, that has been mapped by the probe-tone task (Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979). In the present article, tonality induction is examined from a developmental

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standpoint. The following questions are raised. What are the mental requirements for tonality induction? When in development are these requirements met? Does the process of tonality induction become fixed in adulthood? What experiential factors influence the process of tonality induction? What role does music training play? What makes tonality induction a process worth acquiring?

This article first introduces a conceptualization of tonality induction that is used throughout the following three sections. The first of these sections focuses on the prerequisites for tonality induction in infancy; the second focuses on issues of plasticity and musical exposure beyond infancy; and the third concerns the effects of musical training on tonality induction. Because both music and language are complex acoustical/syntactic systems for which children rapidly develop competence, a parallel with developmental psycholinguistics is occasionally drawn, although the scope of the article prevents a thorough comparison.

A Conception of Tonality Induction

Think of the output of tonality induction as a dynamic mental graph of weights on the 12 octave-collapsed tones of the chromatic scale. The graph contains the information of the standard probe-tone profile (Krumhansl, 1990) and could be organized in the usual way, with the 12 chroma lined up alphabetically along the *x* axis and weights (i.e., ratings) indicated on the *y* axis. However, for most tonal music, a set of seven diatonic tones, related as the cycle of fifths, receives the greatest weights. Therefore, a natural form for the graph entails ordering the 12 chroma as the cycle of fifths in a circular display (or 12-sided polygon [dodecagon]) as shown in Figure 1. With this arrangement, twelve 30° segments represent the 12 pitch chroma, and every set of 7 adjacent chroma represents a diatonic scale. Weights or activity on the display reflect the prominence of a particular chroma in the unfolding music. Activity is depicted in the figure by the height of the darkened portion (or total filled area) of each segment of the dodecagon. A selection of tonal music typically will activate primarily only a portion of such a display.

This display has several advantages. Spread (leakage) of activation to adjacent chroma (adjacent fifths) would still maintain the general effect of the tonality. Moreover, having no beginning or end, the octave-collapsed circular representation does not need reconfiguration with respect to a starting note as the key changes, in contrast to a linear representation with consecutive chroma increasing along the *x* axis from an arbitrarily chosen starting chroma in the alphabet (e.g., C C♯ D ... B). Finally, near-key modulations require simple shifts in weights (i.e., spread of activation) across adjacent segments, and the pattern of the summed weights of successive

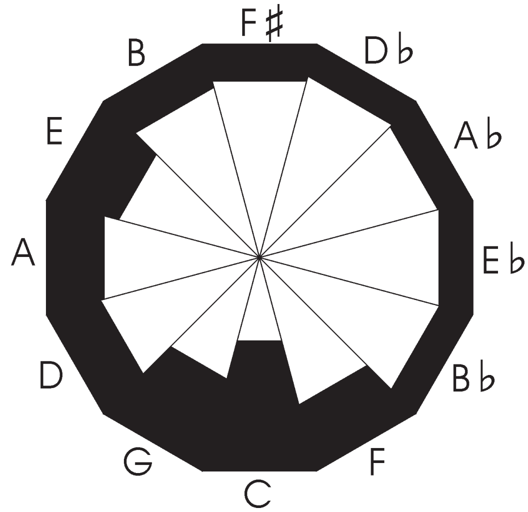

Fig. 1. Circular tonality induction display exploiting the cycle-of-fifths structure. The dark area reflects activated chroma representing the inferred set of pitches associated with the induced tonality; the white area reflects inactivity of chroma outside the primary tonality (example is based on ratings from the major key context, Krumhansl & Kessler, 1982).

modulations produces a smooth activation contour that is still highly differentiated from representations of distant tonalities. The simplicity of this structure suggests that it could develop early in life.

Consider, for argument's sake, that at birth, the coordinates of the tonality display (or a place for them) exist neurologically but the display itself is blank. When a complex tone of a melody is first played, the chroma of the fundamental of that tone and its prominent overtones (say, the first six) are represented in the display. Thus, for a tone with a fundamental of C, the available chroma (C, C, G, C, E, G) give C the greatest weight and E the least in accordance with their relative prominence in the overtone series. Assume that the information persists during the subsequent presentation of a second tone. This second tone (for example, G, with its overtones B and D) also leaves its imprint on the display, and so on for the remaining notes of the piece. Any traditional tonal work would result in a longtime averaged chroma spectrum that resembles the typical tonal hierarchy. See, for example, Leman's (2000, p. 490, Figure 4) global pitch images of the C-major scale. In other words, by virtue of the redundancies of Western-European music, the pattern of activity on the display is nonrandom. As typically described, the pattern has regular properties: one tone–the tonic–having the greatest activity followed by tones a perfect fifth and a major third from it; tones a perfect fourth, major second, major sixth, and major seventh from the tonic having somewhat less weight, and the remaining nondiatonic tones receiving the least weight of all (Krumhansl, 1990).

Such a system requires a simple memory accumulator, although other more complex aspects of memory could serve it well. A detailed discussion of auditory memory is beyond the scope of this article, but a few remarks are appropriate. Behavioral (Cowan, 1995) and neurophysiological (Näätänen & Winkler, 1999) standpoints agree that there are several auditory memory systems differentiated by their time base and function. Cowan (1995) distinguishes sensory and short-term memory and also differentiates two types of sensory memory. The shorter provides an exact sensory afterimage for less than 0.5 s (a window of two quarter notes at allegro tempo). The longer lasts up to 10 or 20 s and "is perceived as a clear recollection of the sound" (Cowan, 1995, p. 61). Such a time span could easily represent many bars of music, far in excess of the minimum required to represent tonality (e.g., Cohen, 1991). Although the time span for this longer auditory sensory memory coincides with that for short-term memory, the two are not equivalent: sensory memory requires external sensory support, but short-term memory can be generated on the basis of prior knowledge and imagery. Because infants lack prior knowledge, sensory memory alone is sufficient in theory to represent tonality (even if sensory memory were a fraction of the adult duration).

According to Baars (1997) and Cowan (1995), attended items are activated from an implicit preattentive subset, itself activated but out of conscious awareness (Baars, 1997; Cowan, 1995).[1] It would seem that tonality falls into the latter preattended category and could be served by sensory memory. Whereas a listener is not necessarily conscious of tonality, there is awareness of surface features of melody, rhythm, tempo, contour, and timbre.[2] Tonality acts as a backdrop against which items in short-term (working) memory take center stage (to use Baars' theatre metaphor of consciousness). One of the general points introduced and emphasized in this article is that tonality induction helps to overcome short-term memory (conscious) capacity limitations for music awareness. Tonality induction forms a good part of the iceberg beneath the musical surface, particularly for pitch.

Information from sensory or short-term memory, if repeated or rehearsed, can become represented in long-term memory which, for all intents and purposes, is unlimited. Thus, the biased probabilities of the 12 chromatic

1. On the basis of acoustical confusions and word length effects on verbal memory, Baddeley (1986) postulated the phonological loop, an auditory short-term memory distinct from other short-term memory systems such as a visual-spatial sketchpad (Baddeley, 1986). Whether the phonological loop serves music or whether a distinct musical short-term memory is required is unclear (Berz, 1995; Lymburner & Cohen, 1994).

2. A listener might claim to remember a melody but not its tonality, much like an amnesic person who cannot recite a telephone number but proceeds to dial it. It can be argued that singing a melody implies knowledge of its tonality (e.g., songs like "Twinkle, Twinkle Little Star," or "Joy to the World," in which the scale forms a major part of the melody). Cohen (1975, 1978) introduced the concept of inferred sets of pitches to accommodate this unconscious representation of expected tones associated with tonality.

tones in Western music should ultimately enter long-term memory. With greater musical sophistication, particular tonality-defining features, such as an ascending semitone, or a tritone, take on the role of learned cues that can activate a specific tonality pitch distribution (Butler, 1989). Several models of tonality induction take memory into account. Vos and Van Geenen (1996) include a memory constraint of a 30-tone window, and Leman (1995) accommodates both sensory and short-term storage. Most models assume a long-term-memory structure representing the acquired tonal hierarchy that assists encoding and memory of music. For this article, we are interested in the adequacy of developing memory systems for tonality induction.

Tonality induction depends on more than memory. The ability to resolve frequency is essential. Analysis of complex tones and sensitivity to sequential order contribute to more sophisticated aspects of tonality induction. It will be argued that tonality induction depends on these prerequisite abilities on the one hand and on mental plasticity (a function of developmental processes), exposure to music of particular styles (a function of culture), and musical performance training (a joint function of culture and predisposition) on the other.

Prerequisites for Tonality Induction

The prerequisites to tonality induction are considered here roughly in order of increasing level of abstraction or memory load of the processes.

FREQUENCY RESOLUTION

Evidence of frequency resolution in infants that is adequate for the decoding of music was nicely shown in a study of pitch matching by Kessen, Levine, and Wendrich (1979). Infants of 6 months of age matched the representation of their self-produced pitch with their representation of an externally produced pitch. Papoušek and Papoušek (1981) corroborated pitch matching to single tones in a case study of their 3-1/2-month-old daughter. Melodic discrimination experiments with 9- to 11-month-old infants also revealed the ability to distinguish a frequency difference of a semitone (Cohen, Thorpe, & Trehub, 1987; Cohen, Trehub, Thorpe, & Morrongiello, 1984; Trehub, Cohen, Thorpe, & Morrongiello, 1986).[3]

3. Whereas musical frequency resolution in infancy seems adequate for discrimination and categorization of tones into twelfth-octave bins, there is development until the age of 5 years (Schneider & Trehub, 1992). Evoked potential data further suggest that adultlike states of neural processing in the auditory system do not develop until late childhood. Wightman and Allen (1992) noted marked individual differences in frequency resolution in a study of children from 3 to 9 years old, with no child in the youngest age group matching adult performance.

RESOLUTION OF OVERTONES AND PROCESSING OF COMPLEX TONES

For adults, pitch perception of complex tones (tones having more than one component frequency) entails a pattern recognition and inference process based on analysis of the component overtones (e.g., the missing fundamental must be inferred). Infants in discrimination studies categorize tones that have the same fundamental but different overtone structure similarly to how adults categorize them (Clarkson, 1992). Further evidence of infants' processing of overtones is provided by Pick, Gross, Heinrichs, Love, and Palmer (1994), who showed that infants between the ages of 7 and 9 months could categorize sounds of some musical instruments. It is important to point out that overtones are analyzed in infancy because the overtones in just one tone provide considerable information for tonality induction, as earlier discussed with regard to neighboring chroma areas in Figure 1. The inference process associated with pitch perception of complex tones is also consistent with the "induction" part of tonality induction.

HARMONIC RELATIONS BETWEEN NOTES

In analyzing their infant's vocal productions, Papoušek and Papoušek (1981) noted a preference for tones around a central tone up to the age of 6 months. At 11 months, 50% of a long melodic monologue represented notes from the F-major scale (particularly, F, A, C, D, F). They concluded that "Obviously, the production of tones during the second half-year of life was influenced by the preference of tones belonging to harmonic series and tonal music" (p. 187). They related difficulties with certain intervals to instability of the 7th and 11th harmonics (p. 199). Their view of the diatonic scale as an "innate, biologically determined universality" (p. 213) coincided with that of Bernstein (1976), to whom they refer. The privileged position of the diatonic small ratios has been shown in developmental studies for octaves (Demany & Armand, 1984; Krumhansl & Jusczyk, 1990, as described by Krumhansl, 1990); the major triad (Cohen et al., 1987), and other simple ratios (Schellenberg & Trainor, 1996; Trainor, 1997; Trainor & Trehub, 1993; Zentner & Kagan, 1996).

CHROMA CATEGORY ACCUMULATION (MEMORY)

Musical information flows as a continuous acoustical stream. Tonality induction, at least in the simple case, depends on tallying the evidence for chroma categories within the stream. Cohen (1986) and Cohen and Trehub (1987) reported the ability of infants to retain a set of tones comprising a sequence. In these studies, the three tones of one major triad were presented in random orders as a standard background such that incorrect comparison sequences were discriminated on the basis of tones that differed by one or two semitones. The ability to do this task is supported by a tonality induction process like the one described earlier whereby a longtime averaged chroma representation of the three tones of the triad readily contrasts with chroma outside this set.

Similarly, Schellenberg and Trehub (1999) conducted a study that showed results consistent with the view that infants map a set of tones in memory and benefit from the increased stability offered by repeated tones. In that study, infants retained a short sequence that began and ended on the same note better than they retained a sequence in which these two notes differed by just a semitone. Schellenberg and Trehub argued that the benefit reflected a general processing strategy rather than the effect of acculturation. The benefits of repetition are consistent with a tonality-induction process that establishes a stable representation of repeated pitch items. As Cowan (1995) states, "the ease of attending to an item can be said to depend on how much it is already activated" (p. 93).[4]

The storage of repeated auditory events is required for tonality induction; in the case of tonality, what is stored is the set of tones presented in music. It is therefore interesting to note a parallel ability for accumulating acoustical information in the speech context. As reported by Jusczyk (1998), 8-month-old infants who were exposed to a repeated word subsequently attended longer to sentences that contained the repeated word than to sentences that did not. After only 30 s of familiarization, the effect lasted a period of 24 hours (see also, Mattys, Jusczyk, Luce, & Morgan, 1999).

TEMPORAL REGULARITY

Some cues to tonality are sequential, for example, the leading-tone-to-tonic sequence is more predictive of the tonality than the reverse order (Cohen, 1975; Cuddy, Cohen, & Mewhort, 1981). Infants also demonstrate sensitivity to temporal characteristics of musical sequences. Krumhansl and Jusczyk (1990) and Jusczyk and Krumhansl (1993) illustrated infants' attentional preferences for conventionally timed phrases of music excerpts by Mozart over phrases with unnatural timing. Saffran, Johnson, Aslin,

4. Schellenberg and Trehub's (1999) evidence for equal performance for the major and diminished triad is at first difficult to reconcile with other evidence of major-triad advantages on tasks requiring memory (Cohen et al., 1987; Trainor & Trehub, 1993) and the priority in infancy of simple frequency ratios cited earlier. Schellenberg and Trehub's (1999) particular task for infants was exceedingly difficult, as were two other tasks that failed to show priority to tonal sequences (Trainor & Trehub, 1992; Trehub, Schellenberg, & Kamenetsky, 1999). Here sequences were at least 10 tones in length and were transposed. Transposition emphasizes frequency ratio relations, but prevents the advantages of repeated frequencies as is characteristic of the typical musical experience. Hence failing to find these effects in the aforementioned studies is not a serious concern for the idea that infants can induce tonality under normal listening conditions.

and Newport (1999) showed that infants discriminated between short sequences of tones that either violated or obeyed the conditional rules of a preexposure sequence. In the developmental psycholinguistic context, Jusczyk (1998) reported the sensitivity of infants to natural grammatical order to which they have been acculturated. Santelmann and Jusczyk (1998) showed that 18-month-old infants preferred to listen to syllable strings that resembled the sequential structure of English rather than strings incorrectly interpolated at lags of several syllables.

MEMORY CONSTRAINTS

The detection of sequential relations in music and speech requires abstraction over time and comparison with other abstractions in memory. Results of all the studies just described are indicative of memory capacities in infancy. Infant performance is often poorer than that of older subjects in comparable tasks, and this difference may be due to infants' immature memory systems. Well beyond infancy, auditory memory in children systematically increases with age, as shown in psychometric tests, such as Gardner's (1985) Test of Auditory-Perceptual Skills (reviewed by Cohen, 1998), nonverbal sequences (Graham & Cohen, 1996), and verbal memory span (Cowan, 1999). Recent electrophysiological evidence confirms this developmental pattern (Gomes et al., 1999).

ANECDOTAL EVIDENCE OF TONAL AWARENESS IN INFANCY AND EARLY CHILDHOOD

The developing musical vocalization behavior of a few infants has been tracked by several parents who are also behavioral scientists. In one case (Papoušek & Papoušek, 1981), tonality induction in infancy was evident in the patterns of tones generated and in the accuracy of melodic production memory. Yet, on the basis of two other children's spontaneous singing, and a review of reports from several other investigators such as Moog and Moorhead, Dowling (1984) suggests that evidence for stable tone centers does not emerge until the age of 5 or 6 years, with sensitivity to the intervals of the musical scale developing a year or two later.

PRELIMINARY SUMMARY

Older infants have the necessary prerequisites for tonality induction with respect to frequency resolution, analysis of overtones, pitch inference for complex tones, accumulation of acoustical information, and sensitivity to sequential regularities, and they have the necessary memory systems to support these tasks. Comparisons with language acquisition also suggest that the process of inducing tonality, much like the process of acquiring language grammar, begins early in life. Several other types of data from children and adults, described in the following sections, can provide insight into tonality induction with respect to issues of musical grammar acquisition in the face of declining plasticity and the role of formal musical training.

Tonality and Musical Grammar Acquisition: Plasticity and Style Exposure

The infancy period is associated with both general processing predispositions (Trehub et al., 1999) and enormous plasticity (Baltes, 1997). Plasticity has been a focus of much research in developmental psycholinguistics, and it is useful to consider briefly some of the findings. In the first half year of life, infants are able to discriminate the phonemes that are subsumed into the same functional category in their native language. With exposure to the native language, however, such ability to distinguish these allophones diminishes (Kuhl, 1998; MacWhinney, 1998; Werker & Tees, 1999). Exposure to one's native language establishes categories of functionally equivalent sounds within the language. After around the age of 12 years, it is also difficult to develop a native accent in a second language. The evidence for the early acquisition of phonetic categories is consistent with Chomsky's notion of an early critical period for language acquisition. The phonetic categories are only one part of the grammar that is acquired. Two other major aspects are semantics (e.g., the rapid or fast mapping of vocabulary for concepts) and syntax (e.g., word order and rules of verb formation for tense and person). By the age of 4 years, the child has acquired most of the phonetic, semantic, and syntactic rules of language grammar. What about music and tonality induction?

Whereas tonality is induced in infancy, there can be ever-increasing levels of efficiency of the process. Refining the ability to induce tonality is part of the process of learning the rules of musical grammar for a particular musical style. As Krumhansl (2000) also noted, just as a music theorist must identify the musical key before proceeding with the theoretical harmonic analysis of an unfolding piece of music, similarly, a listener may implicitly induce tonality in order to make the most sense out of the notes of a piece of music. At a simple level, this entails identification of the most important note or notes of the piece through information on duration, repetition, intensity, and position of prominence (primacy/recency). As soon as one note appears as important in the tonality display of Figure 1, tonality is induced. The cues to tonality (e.g., repetition, accent patterns) at the same time can characterize a musical style or vernacular. Knowledge of the style could serve as a shortcut to tonality induction.

Some recent research suggests that children have an early sensitivity to music stylistic rules. An honors thesis by Betty Bailey (1999) reveals that young children encode the styles of popular music to which they have had most exposure during their short lives but they also encode new styles easily. In the study, children of mean age of 7 years, older children of mean age 12 years, and a control group of young adults were presented with four examples of popular music representing each of the past 10 decades. Children in the youngest age group rated (on a 7-point scale) their preference for these excerpts. Some of the children in the older age group rated preference, and the remaining older children and older adults rated familiarity of the excerpts. For all subjects, the music of recent decades was preferred and was most familiar (for those groups that rated familiarity). Preference and familiarity ratings were highly correlated. In a subsequent surprise recognition task, subjects in all age groups were able to distinguish previously presented from new examples of excerpts from each of the 10 decades. Recognition performance improved with age. Mean d'—a measure of sensitivity independent of response bias, derived from signal detection theory (cf. Macmillan & Creelman, 1991)—was 1.11, 1.81, and 2.95 for the young children, preadolescents, and young adults, respectively). Adults recognized the more recent music better. Unlike the adults, the youngest children's recognition scores were not correlated with their preference pattern. In other words, although the youngest children showed preference for recent music (to which they had been most frequently exposed), this familiarity had no bearing on their recognition. One of the interpretations of this finding is that greater mental plasticity keeps young brains open to unfamiliar musical redundancies. Although young children like what they already know, they are able to learn new relations quickly. May (1986), in a review of style preference in children, also concluded that children before the first grade have a greater openness to musical styles than older children have.

Although this is not a direct test of tonality induction, it bears on the question of plasticity and the sensitivity to musical patterns that influence tonality induction. Other research along these same lines with older adults (Clyburn & Cohen, 1996; Cohen et al., 1995) has revealed preference for music of prior decades in late life and superior recognition ability for music associated with the earlier years. The data from the young and older subjects led to a simple model of musical grammar acquisition in which plasticity plays a role. Governed by plasticity, the model predicts that in later life when mental plasticity is reduced for music (and everything else, Baltes, 1997), grammar for the old styles is preserved but does not serve the new styles well; hence music in the new styles is both poorly encoded and poorly retained. The representation of the plasticity model of music grammar acquisition (Figure 2) shows how knowledge of an early acquired grammar stops the processing of newer styles of music while accepting older styles

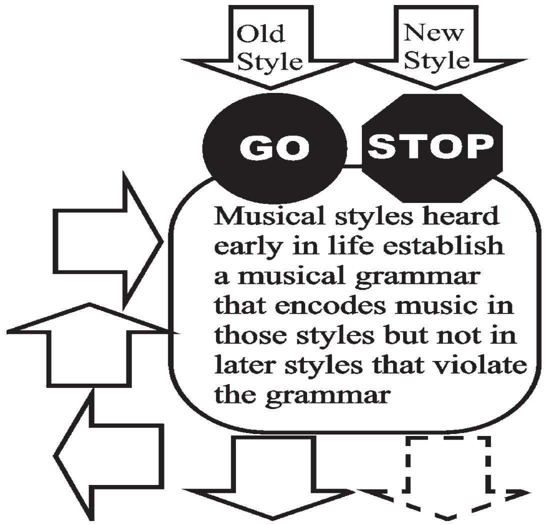

Fig. 2. Plasticity model of musical grammar acquisition.

for encoding, processing, and leaving their memory trace (as reflected by the cyclic arrow pathway). Such a model would reduce the flexibility of long-term-memory representations of tonality with increasing age, explaining why older persons would be more resistant to novel tonalities that might characterize more recent music (Cohen, Bailey, & Clyburn, 2000; see also Rubin, Rahhal, & Poon, 1998).

Musical Training and Tonality Induction

The recognition study just described also compared performance for musically trained and less trained young adults. The musically trained listeners recognized more excerpts from early decades than did the less trained listeners. Many other studies reveal superior performance by musically trained listeners. Even musically trained older adults fare better than untrained older subjects in a melodic memory task (Cohen & Trehub, 1990; Halpern, Kwak, Bartlett, & Dowling, 1996). With regard to tonality specifically, Vos and Verkaart (1999) showed superior mode classification in musically trained subjects. Performance training may partially override declining plasticity beyond adolescence because performance engages so much more of the brain than passive listening. Social-interactionist theories of language acquisition (e.g., Bruner, 1983; Snow, 1999) attribute importance to speech production as opposed to passive speech perception. Music performance training may assist in effectively “shaping the distribution of attention,” a concept proposed by Nusbaum and Goodman (1994) as an approach to understanding the learning of linguistic structure. Further evidence of the influence of music performance experience in tasks that exploit tonality is provided in three diverse types of experiments: (1) absolute judgment, (2) pitch comparison memory, and (3) the probe-tone task.

ABSOLUTE JUDGMENT OF MICROTONAL MELODIES

Many studies show the benefits of diatonic structure on memory for melodies (Cohen, 1975, 1982; Cohen et al., 1987; Cohen, Trehub & Thorpe, 1989; Cuddy, et al., 1981; Cuddy, Cohen & Miller, 1979; Dewar, Cuddy, & Mewhort, 1977; Tillman, Bigand, & Madurell, 1998; Trehub et al., 1986, 1999; Wilson, Wales, & Pattison, 1997). The benefit might result from lifelong exposure to diatonicism or it might result from the presence of small integer ratios. To separate these two possibilities, a study was conducted whereby small ratios were embedded in an unfamiliar otherwise nondiatonic context (Cohen, 1994). A microtonal scale was selected as opposed to a scale with larger intervals because deviations from the larger intervals might be categorized as familiar diatonic intervals, much like allophones are categorized similarly even though they are physically different. An absolute judgment task was used to determine the benefits of small integers and musical training on pitch memory in an unfamiliar context.

The standard absolute judgment task entails a brief training phase during which the items to be judged are presented in a systematic order. In this case, nine tones N_i ($i = 1 \ldots 9$) separated from each other by one-third of a semitone formed the No-Context set. Subsequently, the listeners heard each of these tones randomly presented 36 times and were required to identify them by number, where 1 represented the lowest tone and 9 the highest. (The experiments entailed nine different conditions, only two of which are described here: No-Context and Tuned-Context.) The experiment was executed once with sine tone stimuli and once with complex tones, using different groups of musically trained and untrained subjects in each experiment and producing similar results for the two timbres. Performance in the No-Context condition did not differ with training and was poor as shown in Figure 3 for sine tones.

In the Tuned-Context condition, each of the nine notes (N_i, $i = 1 \ldots 9$) of the microtonal set was embedded as the middle note of a five-note sequence resembling an ascending-descending major triad: T_1 T_2 N_i T_4 T_5; where $T_1 = T_5 =$ *doh*; $T_2 = T_4 =$ *me*; and, from the microtonal scale, $N_6 =$ *soh*. Thus, T_1 T_2 N_6 comprised a major triad with frequency ratios approximating (Expt. 1) or equal to (Expt. 2) 4:5:6. The sixth note (N_6) of the microtonal set of nine tones made a special relation (a major-triad melody, *doh me soh me doh)* with the four exterior context tones, and this special relation could potentially mark this five-note melody as a memorable anchor (Figure 4).

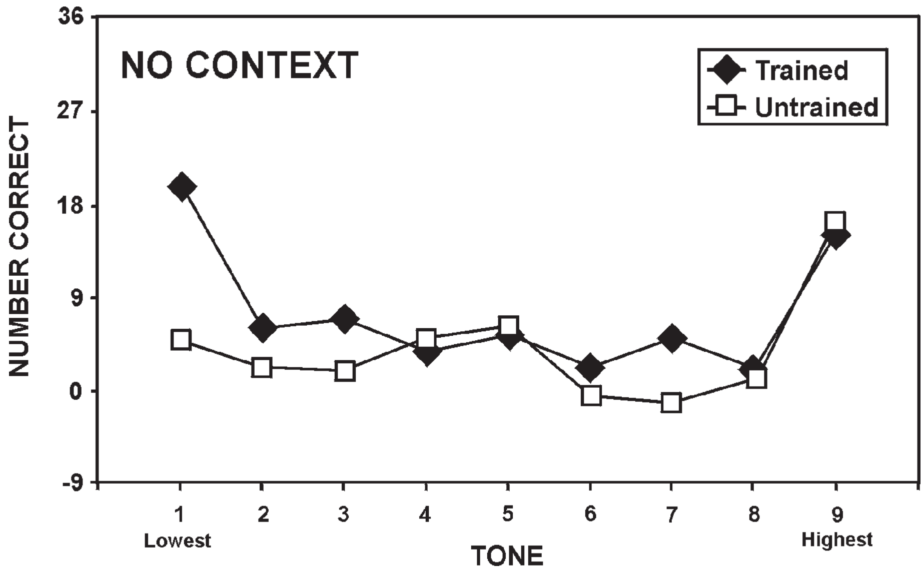

Fig. 3. Mean identification performance in the No-Context condition for each of nine tones for the musically trained and untrained groups.

The remaining eight melodies were less consonant; T_1 T_2 N_1 approximated a minor triad and T_1 T_2 N_9 an augmented triad. The task of the listener was to identify by number (1 … 9) each of the nine melodies that differed only in the central tone, N_i (i = 1 … 9). Each of the nine melodies was presented in a random order 36 times. Performance in the Tuned-Context condition improved over the No-Context condition for the musically trained listeners but not for the untrained (Figure 5). Given the redundancies in each task, the actual information in the No-Context condition and the Tuned-Context condition is identical. By using the familiar major-triad anchor, the musically trained listeners reduced the information load.

Here is a case where sensitivity to the major triad relations benefited only the group that had many years of music performance training and only in the condition where knowledge of the major triad could be used to advantage. The cue to which this group was sensitive was the major triad relation, a relation that is critical to tonality induction (see also Parncutt, 1999). Thus, it would not be surprising to see other effects of music training on tasks entailing tonality induction, as is examined in the next section.

Music Training and the Interpolated-Pitch-Comparison Task

Frankland and Cohen (1996) examined the ability of listeners differing in musical training to compare the pitch of two tones separated by a three-

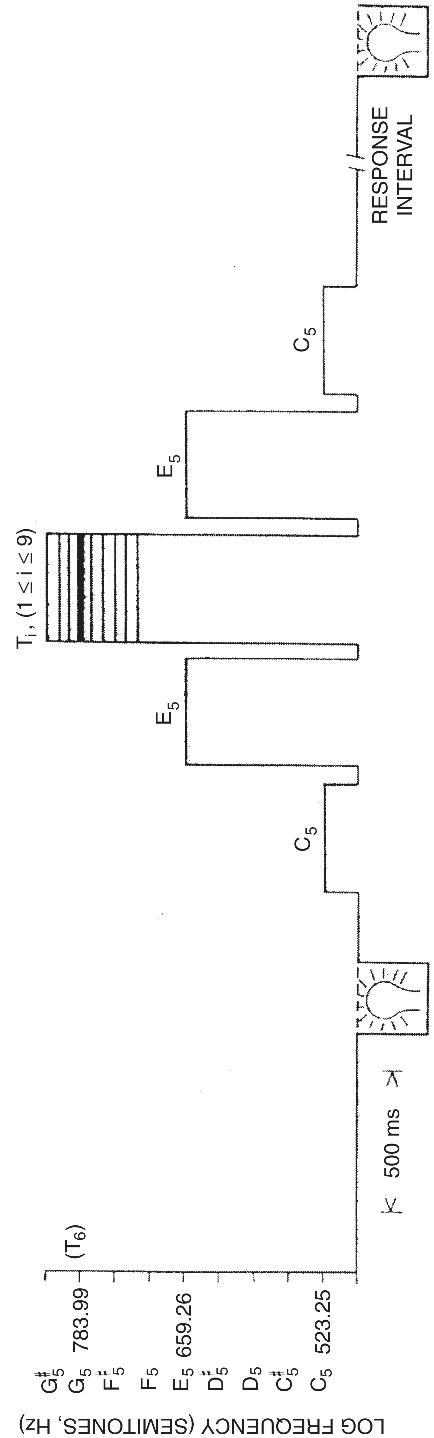

Fig. 4. Representation of the Tuned-Context stimulus conditions.

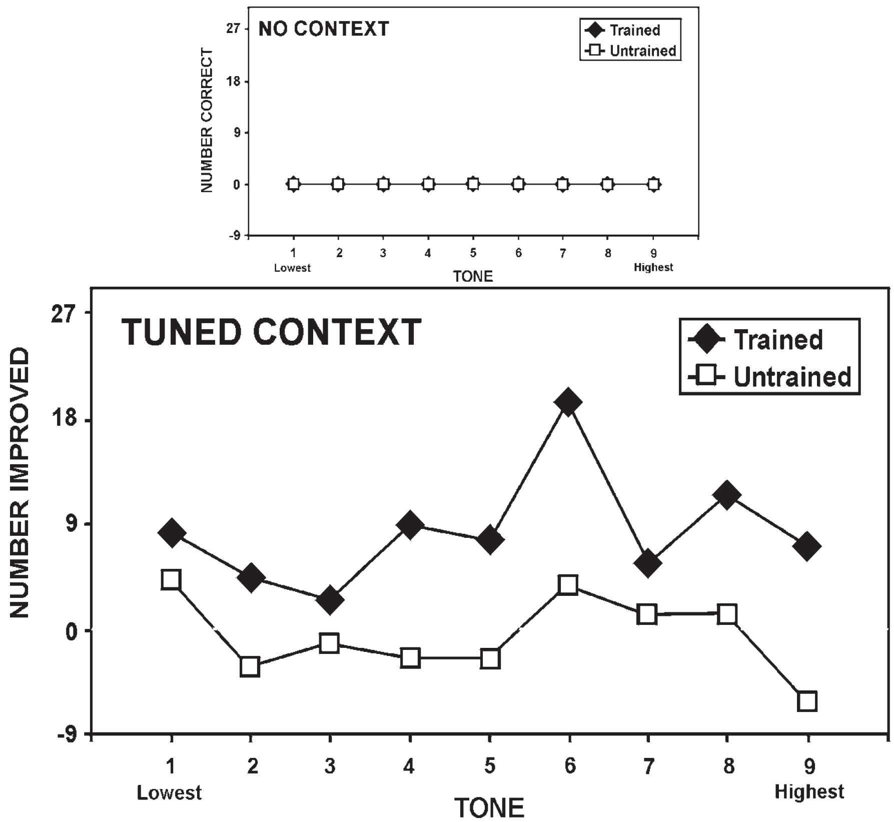

Fig. 5. Improvement in mean identification performance in the Tuned-Context condition for each of nine melodic stimuli for the musically trained and untrained groups. For comparison, the No-Context condition data (from Figure 3) are shown scaled to 0 correct as the baseline against which the Tuned-Context data are compared.

note major or minor triad. Subjects judged whether the comparison (last) tone was the same as the standard (first) tone and were to ignore the intervening sequence. The standard and comparison tones were either identical or differed by one semitone. Krumhansl (1979) used a similar interpolated pitch memory paradigm to compare two levels of stability, tonal versus atonal. The design of the stimulus set in the present study offered 14 gradations of tonal stability for examination. Stability of the first (standard) tone was hypothesized to depend on the place of the tone in the tonal hierarchy derived from tonality induction for the first 4 tones of the trial.[5] Some of

5. Cohen (1977, 1991) reported that the first four note-events from the Bach Preludes from the *Well-Tempered Clavier* were sufficient to cue musically trained subjects as to Bach's designated key. The key-finding algorithm of Krumhansl and Schmuckler (described in Krumhansl, 1990) also matched Bach's key well on the basis of these limited cues. In these compositions, Bach typically provided the tonic and major-triad tones and no nondiatonic notes.

the conditions contained strong cues to tonality (e.g., C C E G), whereas others did not (e.g., C C♯ E G♯). Best-fitting key and key strength were derived for each four-note condition from two models based on the key-finding algorithm of Krumhansl and Schmuckler. A measure was derived of the stability of the first tone in the context of the quantified best-fitting key and its key strength. Memory was considered to be proportional to measured stability for that tone (see Shmulevich & Yli-Harja, 2000, for a similar rationale and application of the key-finding algorithm). The Highly Trained group had received 8 or more years of musical instruction, the Low Trained group had received between 2 and 8 years of musical instruction, and the No Training group had received no musical instruction. Performance overall increased with musical training (from 0.65, to 0.75, to 0.87 mean proportion correct). The models based on the key-finding algorithm were successful in predicting the performance for the two groups with musical training but not for the group of untrained listeners. The effects of tonality, in short, were minimal for the group without training. This suggests that sensitivity to tonality qualitatively changes after 2 years of musical training. Tonality may promote higher performance for the trained groups by stabilizing memory for the standard tone when tonality cues are available.

MUSIC TRAINING AND THE PROBE-TONE TASK

One of the most direct tests of tonality induction is the probe-tone task. Given the previous evidence for effects of training in tasks involving tonality, effects here might also be expected. Results, however, are mixed. Krumhansl and Shepard (1979) initially reported effects of musical training in this task but later Krumhansl (1990) suggested that training differences might have reflected differences in approaches or strategy in the task rather than representation of the tonal hierarchy. Cuddy and Badertscher (1987) reported no effects of training in young adult groups that produced prototypical tonal contexts (normalized data). In their data for children between the ages of 6 and 12 years, Cuddy and Badertscher found no evidence of developmental change across three grade levels, and extraction of those subjects with music training did not influence the pattern of the prototypical profiles produced. Using a slightly different technique, Krumhansl and Keil (1982) had found less-differentiated profiles in children than in adults. Brown, Butler, and Jones (1994) reported no effects of musical training in a probe-tone task that was designed primarily to investigate the role of rare intervals. In an honors thesis, Chris Blanchard (1995) compared the performance of listeners with 10 years of music training with the performance of listeners who had no musical training, in a replication of the paradigm of Brown et al. (Cohen & Blanchard, 2000). The resulting probe-tone profiles revealed more differences associated with training than the research by Brown et al. (1994) might suggest.[6] Frankland and Cohen (1990), in a modified probe-tone task (dichotomous response), produced 12 different groups in a cluster analysis of the profiles. There was some evidence for a more detailed hierarchy for the highly trained group, although the effect was not consistent. Similarly, Jordan (1987), with a sample of just 12 listeners and a probe-tone task examining 48 divisions of the octave, uncovered two profile types associated with two levels of musical training and two unclassifiable profiles associated with no musical training. Evidence for music training effects from different laboratories is unequivocal with respect to the development of the tonality induction process on the one hand and the notion of universality shared by all listeners regardless of training. The acquisition and examination of raw data of individual subjects differing in age and training level is needed until training effects are better understood.

Conclusion

We return now to the questions raised at the beginning of this inquiry into the development of tonality induction processes. First, what are the mental requirements for tonality induction? Our review suggests that tonality induction requires a variety of perceptual-cognitive abilities: to resolve frequency, infer the pitch of complex tones, encode harmonic relations between tones (especially those approximating small integer ratios), accumulate chroma categories represented by the unfolding music, abstract sequential relations, and remember auditory events on different time scales ranging from seconds to days.

Second, when in development are these requirements met? Assuming that tonality induction partially underlies the ability to attend to the musical surface, it is not surprising to find that the prerequisites for tonality induction are in motion by the first year of life. The process itself may not necessarily be all that complex but may aid more complex processes. To use the concept of Nusbaum and Goodman (1994) from their context of learning linguistic structure, tonality induction may be part of the "process

6. The ordinal pattern of the profiles differed for the two training groups for each context, and training interacted with tone and tonal context pattern (major, diminished, and diatonic scale). The tone and context interaction was significant only for the trained group. In correlations with the classic profile of Krumhansl and Kessler (1982), correlation with the major triad was higher for the trained group. Correlations between profiles for the training groups were not significant for the diminished triad. In the study by Brown et al. (1994), differences in training groups may have been too small to affect performance. As pointed out by Auhagen and Vos (2000), their method of classifying subjects on the basis of performance on a tonality task was questionable.

of shaping the distribution of attention," enabling children and ultimately adults to encode long sequences of musical information in order to appreciate the musical nuances.

Third, does this development of tonality induction become fixed in adulthood? In this article, I have also argued that tonality induction processes, like linguistic processes, may benefit from neural plasticity early in life or conversely be constrained by declining plasticity in later years. It has been argued that by 7 years of age, children prefer musical styles to which they have been exposed but remain open to and able to retain information about music in any style. In contrast, older adults prefer music from earlier in their lives and show a priority for this music in recognition memory.

Fourth, what experiential factors influence the process of tonality induction? Given the developmental course of neural plasticity and, with respect to music, the postulated plasticity model of music grammar acquisition, the development of long-term memory that provides a shortcut to tonality induction depends on the amount and type of music-style exposure in early years.

Fifth, what role does musical training play? From the research on absolute judgment and the interpolated pitch memory task, discussed in the preceding section, music training appears to influence listeners' ability to exploit tonality cues in the aid of memory. In an absolute judgment task, young adults with musical training used what they already knew to help them represent new relations, but they did not readily map sets of tones that lacked familiar musical (small-integer) structure. Similarly, Oram and Cuddy (1995, p. 114) reported that for a probe-tone task "responsiveness to novel pitch-distributional information was most evident, not, as might be expected, in the absence of tonal-harmonic resources, but rather in conditions where tonal-harmonic resources could most be engaged," and this was particularly true for musically trained listeners. In memory tasks, tonal stability predicts performance for subjects with musical training (Frankland & Cohen, 1996). In tonality tasks that require low memory load, such as the probe-tone task, the role of musical training is not as clear.

Finally, what makes tonality induction a process worth acquiring? This article began with a quotation from Jerome Bruner that arose in connection with his paper entitled "The Ontogenesis of Speech Acts." Bruner says that exposure to language is not enough to learn it. Something else is needed to make language worth acquiring. That something is linguistic interaction with the world. This raises a further question: whether tonality induction is simply a passive process dependent on exposure to music. Vocal production and vocal interaction with self and others could play a role, as suggested by references to vocal production data (e.g., Dowling, 1984; Papoušek and Papoušek, 1981) in the present article. Singing to infants is a ubiquitous activity of all societies but has typically been neglected by behavioral scientists (Trehub & Trainor, 1998). Infancy and early childhood are periods of much exploratory vocalization with and without caregiver interaction. Therefore, consistent with Bruner and other language social interactionists, it is suggested that vocal interaction and vocal production might make tonality induction worth acquiring. The benefits of the early involvement of the motor system during production may further relate to the evidence for effects of music training observed during the rest of life.

The paucity of data on spontaneous musical vocalizations contrasts sharply with a large, internationally recognized data base of language transcripts from hundreds of children throughout the world, known as CHILDES (the Child Language Data Exchange System, MacWhinney, 1995). Given the discrepancy in the evidence for production of a central reference tone in infancy and in the importance of small ratios in early singing, a data base might be helpful for understanding the early development of tonality induction. Similar to Roger Brown's initial systematic sampling of the speech of three children, melodic productions of children could be sampled instead. Dowling and the Papoušeks conducted similar case studies, but what is suggested here is a standardized protocol and a public repository that uses CHILDES as a model for a Child Music Data Exchange System (CHIMES). Increasing practicality of digital-audio storage lends feasibility to such an idea and might further resolve questions raised in this article about the ontogeny of tonality induction within and among individuals and cultures.[7]

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