# 5 Absolute Pitch

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## I. Introduction

In the summer of 1763, the Mozart family embarked on the famous tour of Europe that established 7-year-old Wolfgang's reputation as a musical prodigy. Just before they left, an anonymous letter appeared in the *Augsburgischer Intelligenz-Zettel* describing the young composer's remarkable abilities. The letter included the following passage:

> *Furthermore, I saw and heard how, when he was made to listen in another room, they would give him notes, now high, now low, not only on the pianoforte but on every other imaginable instrument as well, and he came out with the letter of the name of the note in an instant. Indeed, on hearing a bell toll, or a clock or even a pocket watch strike, he was able at the same moment to name the note of the bell or timepiece.*

This passage furnishes a good characterization of absolute pitch (AP)—otherwise known as perfect pitch—the ability to name or produce a note of a given pitch in the absence of a reference note. AP possessors name musical notes as effortlessly and rapidly as most people name colors, and they generally do so without specific training. The ability is very rare in North America and Europe, with its prevalence in the general population estimated as less than one in 10,000 (Bachem, 1955; Profita & Bidder, 1988; Takeuchi & Hulse, 1993). Because of its rarity, and because a substantial number of world-class composers and performers are known to possess it, AP is often regarded as a perplexing ability that occurs only in exceptionally gifted individuals. However, its genesis and characteristics are unclear, and these have recently become the subject of considerable research.

In contrast to the rarity of AP, the ability to name relationships between notes is very common among musicians. Most trained musicians have no difficulty in naming the ascending pattern D-F♯ as a major third, E-B as a perfect fifth, and so on. Further, when given the name of one of these notes, they generally have no difficulty in producing the name of the other note, using relative pitch as the cue. Yet most musicians, at least in Western cultures, are unable to name a note when it is presented in isolation.

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The rarity of AP presents us with an enigma. We can take color naming as an analogy: When we label a color as red, we do not do so by comparing it with another color (such as blue) and determining the relationship between the two colors; the labeling process is instead direct and immediate. Consider, also, that note naming involves choosing between only 12 possibilities—the 12 notes within the octave (Figure 1). Such a task should be trivial for musicians, who typically spend thousands of hours reading musical scores, playing the notes they read, and hearing the notes they play. In addition, most people have no difficulty naming well-known melodies, yet this task is considerably more complex than is naming a single note. It appears, therefore, that the lack of AP is analogous to color anomia (Geschwind & Fusillo, 1966), in which patients can recognize and discriminate colors, yet cannot associate them with verbal labels (Deutsch, 1987, 1992; Deutsch, Kuyper, & Fisher, 1987).

## II. Implicit AP

Reasoning along these lines, it is not surprising that most people possess an implicit form of AP, even though they are unable to name the notes they are judging. This has been demonstrated in a number of ways. One concerns the tritone paradox—a musical illusion in which people judge the relative heights of tones based on their positions along the pitch class circle, even though they are unaware of doing so. In addition, AP nonpossessors can often judge whether a familiar piece of music is being played in the correct key, and their reproductions of familiar melodies can also reflect implicit AP.

### A. The Tritone Paradox

The tritone paradox was first reported by Deutsch (1986). The basic pattern that produces this illusion consists of two sequentially presented tones that are related by a half-octave (or tritone). Shepard tones are employed, so that their note names (pitch classes) are clearly defined, but they are ambiguous in terms of which octave they are in. For example, one tone might clearly be an A, but could in principle be

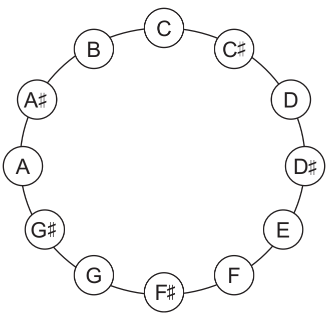


**Figure 1** The pitch class circle.

Concert A, or the A an octave above, or the A an octave below. When one such tone pair is played (say C followed by F♯), some listeners hear an ascending pattern, whereas others hear a descending one. Yet when a different tone pair is played (say, G followed by C♯), the first group of listeners may well hear a descending pattern and the second group an ascending one. Importantly, for any given listener, the pitch classes generally arrange themselves with respect to height in a systematic way: Tones in one region of the pitch class circle are heard as higher, and tones in the opposite region are heard as lower (Figure 2). This occurs even when the spectral envelopes of the tones are averaged over different positions along the frequency continuum, so controlling for spectral effects (Deutsch, 1987, 1992, 1994; Deutsch et al., 1987; Deutsch, Henthorn, & Dolson, 2004b; Giangrande, 1998; Repp & Thompson, 2010). In experiencing the tritone paradox, then, listeners must be referring to the pitch classes of tones in judging their relative heights, so invoking an implicit form of AP. The same conclusion stems from listeners' percepts of related illusions involving two-part patterns; for example, the melodic paradox (Deutsch, Moore, & Dolson, 1986) and the semitone paradox (Deutsch, 1988). These paradoxes of pitch perception are described in Chapters 6 and 7.

## B. Pitch Identification and Production

As a further reflection of implicit AP, musicians who are not AP possessors sometimes remark that they can identify the key in which a piece is played (Sergeant, 1969; Spender, 1980). To explore this claim, Terhardt and Ward (1982) and Terhardt and Seewann (1983) recruited musically literate subjects, most of whom were AP nonpossessors, and presented them with excerpts from Bach preludes that

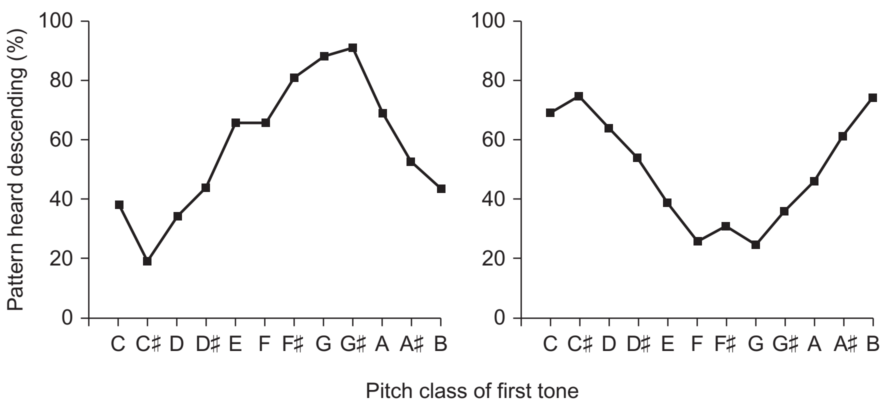


**Figure 2** The tritone paradox as perceived by two subjects. The graphs show the percentages of judgments that a tone pair formed a descending pattern, as a function of the pitch class of the first tone of the pair. The judgments of both subjects displayed orderly relationships to the positions of the tones along the pitch class circle, showing that they were employing implicit absolute pitch in making these judgments.

were either in the original key or transposed by various amounts. The subjects were able to judge to a significant extent whether or not the excerpts were in the original key. Specifically, Terhardt and Seewann (1983) found that the large majority of subjects achieved significant identification performance overall, with almost half of them being able to distinguish the nominal key from transpositions of one semitone. In a further study, Vitouch and Gaugusch (2000) presented AP nonpossessors with Bach's first prelude in C major on several subsequent days. On any one occasion, the piece was presented either in the correct key or as transposed by a semitone, and the subjects were able to determine beyond chance whether they were hearing the original version or the transposed one (see also Gussmack, Vitouch, & Gula, 2006).

An even more general effect was found by Schellenberg and Trehub (2003), who presented unselected college students with familiar theme songs from television shows, and found that the students could discriminate above chance whether or not a song had been transposed by one or two semitones (see also Trehub, Schellenberg, & Nakata, 2008).

A further experiment was carried out by Smith and Schmuckler (2008) to evaluate the prevalence of implicit AP in the general population. The telephone dial tone in North America consists of two tones at 350 and 440 Hz; this has been ubiquitous for decades, so most people in North America have been exposed to the sound on thousands of occasions. AP nonpossessors listened to the dial tone and various pitch-shifted versions, and classified each example as "normal," "higher than normal," or "lower than normal." Although the subjects' judgments reflected a more broadly tuned sensitivity than exists among AP possessors, they could nevertheless judge as "higher than normal" a tone that had been transposed by three semitones.

Implicit AP even occurs very early in life, before speech is acquired. This was shown by Saffran and Griepentrog (2001) who found that 8- to 9-month-old infants were more likely to track patterns of absolute than relative pitches in performing a statistical learning task.

Production tasks have confirmed the presence of implicit AP in the general population. Halpern (1989) asked subjects who were unselected for musical training to hum or sing the first notes of well-known tunes on two separate days, and found that the within-subject variability of the pitch ranges of their renditions was very low. In a further study, Levitin (1994) had subjects choose a CD that contained a popular song with which they were familiar, and then reproduce the song by humming, whistling, or singing. The songs had been performed by only one musical band, so presumably had been heard in only one key. On comparing the pitches of the first notes produced by the subjects with the equivalent ones on the CD, Levitin found that when tested with two different songs, 44% of the subjects came within two semitones of the correct pitch for both songs. In a further study, Bergeson and Trehub (2002) had mothers sing the same song to their infants in two sessions that were separated by at least a week, and based on judges' estimates, their pitch ranges in the different sessions deviated on average by less than a semitone.

# III. Genesis of AP

Given that AP is rare in the Western world, there have been many speculations concerning its genesis. These fall into three general categories: first, that the ability can be acquired at any time through intensive practice; second, that it is an inherited trait that becomes manifest as soon as the opportunity arises; and third, that most people have the potential to acquire AP, but in order for this potential to be realized, they need to be exposed to pitches in association with their note names during a critical period early in life. All three views have been espoused vigorously by a number of researchers.

## *A. The Practice Hypothesis*

Various attempts have been made to acquire AP in adulthood through extensive practice, and in general, these have produced negative or unconvincing results (Cuddy, 1968; Gough, 1922; Heller & Auerbach, 1972; Meyer, 1899; Mull, 1925; Takeuchi & Hulse, 1993; Ward, 1999; Wedell, 1934). An unusually positive finding was described by Brady (1970)—a musician who had begun piano training at age 7, and who tested himself in a single-case study. He practiced with training tapes for roughly 60 hours, and achieved a success rate of 65% correct (97% correct allowing for semitone errors). While impressive, Brady's unique finding underscores the extreme difficulty of acquiring AP in adulthood, in contrast with its effortless, and often unconscious, acquisition in early childhood.

## *B. The Genetic Hypothesis*

The view that AP is an inherited trait has had spirited advocates for many decades (Athos et al., 2007; Bachem, 1940, 1955; Baharloo, Johnston, Service, Gitschier, & Freimer, 1998; Baharloo, Service, Risch, Gitschier, & Freimer, 2000; Gregersen, Kowalsky, Kohn, & Marvin, 1999, 2001; Profita & Bidder, 1988; Revesz, 1953; Theusch, Basu, & Gitschier, 2009). One argument for this view is that the ability often appears at a very young age, even when the child has had little or no formal musical training. AP possessors frequently remark that they have possessed the ability for as long as they can remember (Carpenter, 1951; Corliss, 1973; Takeuchi, 1989). On a personal note, I can still recall my astonishment on discovering, at age 4, that other people (even grown-ups) were unable to name notes that were being played on the piano without looking to see what key was being struck. Presumably I had received some musical training at that point, but this would have been minimal.

Another argument for the genetic view is that AP tends to run in families (Bachem, 1940, 1955; Baharloo et al., 1998, 2000; Gregersen et al., 1999, 2001; Profita & Bidder, 1988; Theusch et al., 2009). For example, in a survey of 600 musicians, Baharloo et al. (1998) found that self-reported AP possessors were four times more likely than nonpossessors to report that a family member possessed AP.

The argument from familial aggregation is not strong, however. The probability of acquiring AP is closely dependent on early age of musical training (Section III,C), and parents who provide one child with early music lessons are likely to provide their other children with early lessons also. Indeed, Baharloo et al. (2000) has shown that early musical training itself is familial. Furthermore, it is expected that babies who are born into families that include AP possessors would frequently hear musical notes together with their names early in life, and so would have the opportunity to acquire such associations at a very young age, during the period in which they learn to name the values of other attributes, such as color.

A further argument in favor of a genetic (or at least innate) contribution to AP concerns its neurological underpinnings. As described in Section VI, there is good evidence that AP possessors have a uniquely structured brain circuitry (Bermudez & Zatorre, 2009b; Keenan, Thangaraj, Halpern, & Schlaug, 2001; Loui, Li, Hohmann, & Schlaug, 2011; Oechslin, Meyer, & Jäncke, 2010; Ohnishi et al., 2001; Schlaug, Jäncke, Huang, & Steinmetz, 1995; Schulze, Gaab, & Schlaug, 2009; Wilson, Lusher, Wan, Dudgeon, & Reutens, 2009; Zatorre, Perry, Beckett, Westbury, & Evans, 1998), though the role of neuroplasticity in the development of this circuitry remains to be resolved.

Other arguments in favor of a genetic contribution to AP have centered on its prevalence in various ethnic groups. Gregersen et al. (1999, 2001), in a survey of students in music programs of higher education in the United States, found that a high percentage of East Asian students reported possessing AP. However, Henthorn and Deutsch (2007) in a reanalysis of the Gregersen et al. (2001) data found that, considering only those respondents with early childhood in North America, the prevalence of AP did not differ between the East Asian and Caucasian respondents. Yet this prevalence was significantly higher among respondents who had spent their early childhood in East Asia rather than North America. An environmental factor or factors must therefore have been a strong determinant of the findings by Gregersen et al. As is argued later (Section IV,D), there is strong evidence that the type of language spoken by the listener strongly influences the predisposition to acquire AP.

Further evidence with respect to the genetic hypothesis concerns the distributions of AP scores that have been found in various studies. Athos et al. (2007) administered a Web-based test for AP, and obtained responses from more than 2000 self-selected participants. The scores were not continuously distributed and appeared to be bimodal, so the authors concluded that AP possessors constitute a genetically distinct population. However, 44% of the participants in this study qualified as AP possessors—a percentage far exceeding that in the general population—so that self-selection and other problems involved in unconstrained Web-based data collection render these findings problematic to interpret.

Avoiding the problem of Web-based testing, Bermudez and Zatorre (2009a) advertised for musically trained subjects both with and without AP and tested them in the laboratory. When formally tested for AP, some subjects performed at a very high level of accuracy, while others performed at chance. However the performance of a significant number of subjects fell between these two extremes, again providing evidence that AP is not an all-or-none trait. Yet because the subjects were self-selected, the distribution of scores found in this study is also equivocal in its interpretation.

To avoid the problem of self-selection, Deutsch, Dooley, Henthorn, and Head (2009) carried out a direct-test study to evaluate the prevalence of AP among first- and second-year students at the University of Southern California Thornton School of Music. The students were tested in class and were not self-selected. Figure 3 shows the distribution of the scores among the 176 subjects who were Caucasian nontone language speakers, together with the hypothetical distribution of scores based on chance performance. As can be seen, the scores of most subjects were consistent with chance, with the distribution being slightly elevated at the high end; however the scores of a significant proportion of subjects were above chance yet below the generally accepted criteria for AP. Other studies have confirmed that a significant proportion of the population are borderline AP possessors (Athos et al., 2007; Baharloo et al., 1998; Deutsch, Le, Shen, & Li, 2011; Dooley & Deutsch, 2010; Itoh, Suwazono, Arao, Miyazaki, & Nakada, 2005; Loui et al., 2011; Miyazaki, 1990; Oechslin et al., 2010; Rakowski & Morawska-Bungeler, 1987; Wilson et al., 2009).

Returning to the genetic issue, since most complex human traits exhibit a bell-shaped, continuous distribution, with exceptional individuals occupying the tail end of the curve (Drayna, 2007), the distributions of scores found on AP tests are indeed unusual, even though not strictly bimodal. This could reflect a genetic contribution to the predisposition to acquire AP. However other factors, to be described later, would also be expected to skew such distributions. Ultimately, the demonstration of a genetic contribution to AP awaits the discovery of a gene or

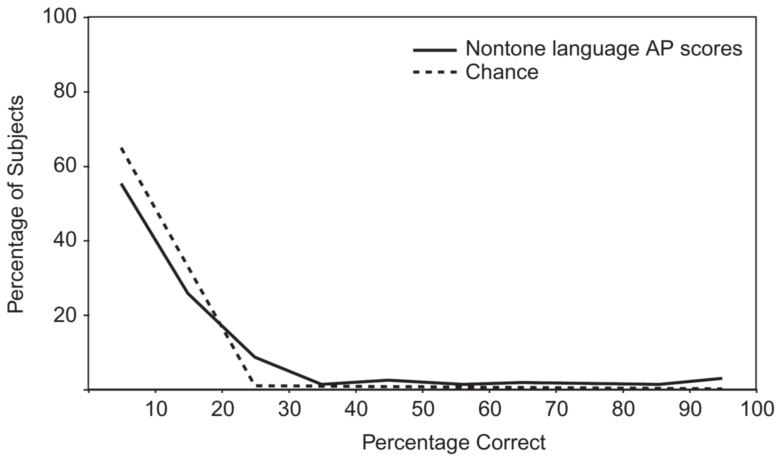


**Figure 3** Distribution of absolute pitch in a population of nontone language speakers. The solid line shows the distribution of scores on a test of absolute pitch among nontone language speaking students in a large-scale study at an American music conservatory. The dashed line shows the hypothetical distribution of scores expected from chance performance. Adapted from Deutsch, Dooley, et al. (2009).

genes that contribute to this trait. As a step in this direction, Theusch et al. (2009) have provided preliminary evidence for a genome-wide linkage on chromosome 8 in families with European ancestry that include AP possessors.

### C. The Critical Period Hypothesis

A large number of studies have pointed to an association between AP possession and early age of onset of musical training (Bachem, 1940; Baharloo et al., 1998, 2000; Deutsch, Henthorn, Marvin, & Xu, 2006; Deutsch, Dooley, et al., 2009; Deutsch et al., 2011; Dooley & Deutsch, 2010, 2011; Gregersen et al., 1999; Lee & Lee, 2010; Levitin & Rogers, 2005; Miyazaki, 1988; Miyazaki & Ogawa, 2006; Profita & Bidder, 1988; Sergeant, 1969; Takeuchi, 1989; Takeuchi & Hulse, 1993; van Krevelen, 1951; Vitouch, 2003; Ward, 1999). Although many of these studies have involved small numbers of subjects, large-scale studies on this issue have also been carried out. Some of these have been surveys, in which respondents stated by self-report whether or not they possessed AP. For example, Baharloo et al. (1998) in a survey of 600 musicians, found that 40% of those who had begun musical training by age 4 self-reported having AP; this contrasted with 27% of those who had begun training at ages 4–6, 8% of those who had begun training at ages 6–9, and 4% of those who had begun training at ages 9–12. (As a caution, we should note that while the correlation with age of onset of musical training found here is impressive, absolute percentages of AP possession derived from self-report of self-selected respondents are likely to be exaggerated.) In addition, Gregersen et al. (1999) in a survey of more than 2000 music students observed that self-reported AP possessors had begun musical training at an average age of 5.4 years.

The dependence on age of onset of musical training indicated in these surveys has been confirmed in large-scale direct-test studies. Deutsch et al. (2006) administered a test of AP to 88 students at the Central Conservatory of Music in Beijing, and to 115 students at Eastman School of Music, using a score of at least 85% correct as the criterion for AP possession. The students were tested in class, with no self-selection from within the target population. As discussed later, there was a large effect of language, with the Beijing group being speakers of Mandarin and the Eastman group being speakers of nontone languages such as English. However there was, in addition, a systematic effect of age of onset of musical training. For the nontone language speakers, among those who had begun training at ages 4–5, 14% met the criterion, whereas 6% of those who had begun training at ages 6–7 did so, and none of those who had begun training at age 8 or later did so. For the tone language speakers, among those who had begun musical training at ages 4–5, 60% met the criterion; compared with 55% of those who had begun training at ages 6–7 and 42% of those who had begun training at ages 8–9. Further large-scale direct-test studies have confirmed the correlation between age of onset of training and the possession of AP (Deutsch, Dooley, et al., 2009; Deutsch et al., 2011; Lee & Lee, 2010), and these are discussed in Section IV,D.

Other studies pointing to the importance of early exposure to musical notes and their names have involved testing children. Russo, Windell, and Cuddy (2003) trained children and adults to identify a single note from among a set of seven possible notes, and found that by the third week of training, the identification accuracy of children aged 5–6 surpassed the accuracy of a group of adults. In another study, Miyazaki and Ogawa (2006) tested children at a Yamaha School of Music in Japan, and found that their pitch-naming scores increased markedly from ages 4 to 7.

### D. Influence of Type of Musical Training

It is often surmised that "fixed-do" methods of musical training are more conducive to the development of AP than are "moveable-do" methods. In fixed-do systems, solfège symbols (do, re, mi, etc.) define actual pitches, being equivalent to C, C♯, D, etc. In moveable-do systems, on the other hand, solfège symbols are instead used to define the roles of pitches relative to a tonic, while letter names (C, C♯, D, etc.) are used to define the actual pitches. One argument that has been advanced in favor of fixed-do methods is that AP is more prevalent in certain countries where fixed-do training is quite common, such as Japan, whereas AP is rare in certain other countries, such as England, where moveable-do training is more common instead. However, in yet other countries where fixed-do training is also common, such as France, the prevalence of AP is again rare, so the argument in favor of fixed-do training based on prevalence of AP in a few selected countries is a problematic one.

Gregersen et al. (2001) noted that a high proportion of East Asians self-reported having AP, but acknowledged that fixed-do training alone could not account for their results. They observed, however, that AP possessors were more likely to have had fixed-do rather than moveable-do training. Yet unfortunately the authors did not take age of onset of musical training into account in their analysis, so their findings could instead have reflected an earlier age of onset of music lessons among those with fixed-do training.

Peng, Deutsch, Henthorn, Su, and Wang (in press) conducted a large-scale direct-test study on 283 first- and second-year students in music departments at three universities in South China: South China Normal University, Guangdong University of Foreign Studies, and South China University of Technology. Again, the students were tested in class, and the subjects were not self-selected. They were administered the same AP test as in Deutsch et al. (2006), and were asked to write down the name of each note when they heard it. Depending on their preference, they could respond either by letter name (C, C♯, D, and so on) indicating moveable-do training, or by solfège name (do, do-sharp, re, and so on) indicating fixed-do training. The expected effect of age of onset was obtained, and interestingly a large effect in favor of moveable-do training was also obtained. For those subjects with an age-of-onset of 9 years or less, the percentage correct on the AP test among the moveable-do subjects was almost double that among the fixed-do subjects. As a further interesting point, a far larger number of subjects responded using letter names than fixed-do solfège names, indicating that moveable-do training methods are highly prevalent in China, where the prevalence of AP is also high.

A more convincing point with respect to type of musical training is that children who are first taught to play on transposing instruments are at a clear disadvantage for the acquisition of AP. For example, a notated C on a B♭ clarinet is played as the note B♭ rather than C, and a notated C on an F horn is played as the note F. Such discrepancies between the viewed and sounded notes would be expected to discourage the acquisition of AP. In addition, in the study by Peng et al. (in press) just described, those subjects who had been trained on Western-style musical instruments substantially outperformed those who had been trained with folk or vocal music.

## IV. AP and Speech Processing

A linkage between AP and speech processing is indicated from various lines of evidence. First, in experiencing the tritone paradox, percepts vary depending on the language or dialect to which the listener has been exposed, particularly in childhood. Second, the critical periods for acquisition of AP and speech have remarkably similar timetables. Third, the neuroanatomical evidence points to a commonality of brain structures that underlie AP and speech processing. Fourth, the prevalence of AP is very high among speakers of tone languages, in which pitch is critically involved in determining lexical meaning.

### *A. Evidence from the Tritone Paradox*

One body of evidence pointing to a linkage between AP and speech concerns the tritone paradox (Deutsch, 1986, 1991, 1992; Deutsch, Henthorn, & Dolson, 2004b; Deutsch et al., 1987; Deutsch, North, & Ray, 1990). As described earlier, judgments of this pattern show systematic relationships to the positions of the tones along the pitch class circle, even though the listeners are unable to name the tones they are judging. Further research has shown that the form of this relationship varies with the language or dialect to which the listener has been exposed (Chalikia & Leinfelt, 2000; Chalikia, Norberg, & Paterakis, 2000; Chalikia & Vaid, 1999; Dawe, Platt, & Welsh, 1998; Deutsch, 1991, 1994; Deutsch et al., 2004b; Giangrande, 1998; Ragozzine & Deutsch, 1994), and also correlates with the pitch range of the listener's speaking voice (Deutsch et al., 1990, 2004b), which in turn varies depending on the speaker's language or dialect (Dolson, 1994; Deutsch et al., 2004b; Deutsch, Le, Shen, & Henthorn, 2009). The tritone paradox, then, provides an example of implicit AP that is closely related to phonological processing of speech.

### *B. Critical Periods for AP and Speech*

The verbal labeling of pitches necessarily involves language, and this leads to the conjecture that the critical period for acquiring AP might be linked to that for acquiring speech. Lennenberg (1967) pointed out that adults and young children acquire a second language in qualitatively different ways. Following puberty, such acquisition is self-conscious and labored, and a second language that is acquired in adulthood is generally spoken with a "foreign accent" (see also Scovel, 1969; Patkowski, 1990). Of particular interest, the aspect of second language that is most difficult to acquire is phonological. Joseph Conrad provides a famous example here. He learned English at age 18, and after a few years of practice produced some of the best works of English literature; nevertheless, his foreign accent was strong enough to prevent him from lecturing publically in English.

Since Lennenberg's book was published, there have been numerous studies of the critical period for speech acquisition (Doupe & Kuhl, 1999; Johnson & Newport, 1989; Newport, 1990; Newport, Bavelier, & Neville, 2001; Sakai, 2005). A few children who had been socially isolated early in life and later placed in a normal environment have been found not to acquire normal speech (Curtiss, 1977; Lane, 1976). Studies of recovery of speech following brain injury provide even more convincing evidence: The prognosis for recovery has been found to be most positive if the injury occurred before age 6, less positive between ages 6 and 8, and extremely poor following puberty (Bates, 1992; Dennis & Whitaker, 1976; Duchowny et al., 1996; Varyha-Khadem et al., 1997; Woods, 1983).

The timetable for acquiring AP is remarkably similar to that for acquiring speech. As noted earlier, AP is extremely difficult to develop in adulthood; yet when young children acquire this ability they do so effortlessly, and often without specific training. This correspondence between timetables suggests that the two capacities may be subserved by a common brain mechanism. Notably, although there are critical periods for other aspects of development, such as for ocular dominance columns in the visual cortex of cats (Hubel & Wiesel, 1970), imprinting in ducks (Hess, 1973), and auditory localization in barn owls (Knudsen, 1988), no other critical periods have been shown to have a similar correspondence with speech and language (see also Trout, 2003). We can note that while speech is normally acquired in the first 2 years of life, formal music lessons can be initiated only when the child is more mature. Extrapolating back, then, from the age at which formal musical training can reasonably be initiated, we can conjecture that if infants are given the opportunity to associate pitches with meaningful words during the critical period for speech acquisition, they might readily develop the neural circuitry underlying AP at that time (Deutsch, 2002).

## C. Neuroanatomical Evidence

Another argument for an association between AP and language concerns their neuroanatomical correlates. One region of particular importance here is the left planum temporale (PT)—an area in the temporal lobe that corresponds to the core of Wernicke's area, and that is critically involved in speech processing. The PT has been found to be leftward asymmetric in most human brains (Geschwind & Levitsky, 1968). Schlaug et al. (1995) first reported that this asymmetry is greater among AP possessors than among nonpossessors, and this finding has been followed up in several studies. In an experiment that specifically supports an association between AP, the left PT, and speech, Oechslin et al. (2010) found that AP possessors showed significantly greater activation in the left PT and surrounding areas when they were engaged in segmental speech processing. Furthermore, Loui et al. (2011) observed that AP possession was associated with heightened connectivity of white matter between regions subserving auditory perception and categorization in the left superior temporal lobe—regions that are considered to be responsible for the categorization of speech sounds (Hickok & Poeppel, 2007). The neuroanatomical substrates of AP are explored in further detail in Section VI.

## D. AP and Tone Language

The argument for a linkage between AP and language is strengthened by consideration of tone languages, such as Mandarin, Cantonese, Vietnamese, and Thai. In tone languages, words assume arbitrarily different meanings depending on the *tones* in which they are enunciated. Lexical tone is defined both by pitch height ("register") and by contour. For example, the word "ma" in Mandarin means "mother" when it is spoken in the first tone, "hemp" in the second tone, "horse" in the third tone, and a reproach in the fourth tone. Therefore when a speaker of Mandarin hears the word "ma" spoken in the first tone, and attributes the meaning "mother," he or she is associating a particular pitch—or a combination of pitches—with a verbal label. Analogously, when an AP possessor hears the note F♯ and attributes the label "F♯", he or she is also associating a particular pitch with a verbal label.

The brain substrates underlying the processing of lexical tone appear to overlap with those for processing phonemes in speech. Although the communication of prosody and emotion preferentially engages the right hemisphere in both tone and nontone language speakers (Edmondson, Chan, Siebert, & Ross, 1987; Gorelick & Ross, 1987; Hughes, Chan, & Su, 1983; Ross, 1981; Tucker, Watson, & Heilman, 1977), the processing of lexical tone is primarily a left hemisphere function. For example, impairments in lexical tone identification have been observed in aphasic patients with left-sided brain damage (Gandour & Dardarananda, 1983; Gandour et al., 1992; Moen & Sundet, 1996; Naeser & Chan, 1980; Packard, 1986). Further, normal tone language speakers exhibit a right ear advantage in dichotic listening to lexical tones (Van Lancker & Fromkin, 1973) and show left hemisphere activation in response to such tones (Gandour, Wong, & Hutchins, 1998).

These lines of evidence imply that when tone language speakers perceive and produce pitches and pitch contours that signify meaningful words, circuitry in the left hemisphere is involved. From the evidence on critical periods for speech acquisition, we can assume that such circuitry develops very early in life, during the period in which infants acquire other features of speech (Doupe & Kuhl, 1999; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Werker & Lalonde, 1988). So we can conjecture that if pitches are associated with meaningful words in infancy, the left hemisphere supports the association between pitches and verbal labels that subserves AP. We can further conjecture that if individuals are not provided with the opportunity to form such associations in infancy or early childhood, they should find AP very difficult to acquire later in life. This line of reasoning could account for the presence of implicit AP combined with the absence of explicit AP in speakers of nontone languages (see also Rakowski & Miyazaki, 2007).

Given this line of reasoning, it was further surmised that tone language speakers employ precise and stable AP templates in enunciating words. As a test of this conjecture, Deutsch, Henthorn, and Dolson (1999, 2004a) gave native speakers of Vietnamese a list of words to read out on two separate days, with the words chosen so that they spanned the range of tones in Vietnamese speech. Then for each spoken word, we took pitch estimates at 5-ms intervals, and from these estimates, we derived an average pitch for each word. Then, for each subject, we calculated the difference between the average pitch for each word as it was read out on the two separate days, and we averaged these differences across words in the list. On comparing these averages across days, we found that the majority of subjects displayed averaged pitch differences of less than 0.5 semitone.

In a further experiment, we presented Mandarin speakers with a list of words containing all four Mandarin tones to read out on two separate days. We found that one-third of the subjects showed averaged pitch differences across days of less than 0.25 semitone and that the Mandarin speakers were as consistent across days as on immediate repetition. However, a control group of English speakers were significantly less consistent in enunciating a list of English words across two separate days. From this, we concluded that the tone and nontone language speakers were processing the absolute pitch levels of speech in qualitatively different ways, and specifically that AP is involved in processing lexical tone.

Burnham and Brooker (2002) came to a related conclusion from a study in which nontone language speakers discriminated pairs of Thai tones that were presented as speech, filtered speech, and violin sounds. In all conditions, AP possessors outperformed nonpossessors in lexical tone discrimination. The authors concluded that absolute pitch level was an important cue to the identification of Thai tones, and they surmised that the superior performance of the AP possessors was due to their having acquired AP during the speech-related critical period.

Continuing along these lines, we can conjecture that speakers of tone language acquire AP for musical tones as though these were the tones of a second tone language. Based on studies of acquisition of a second language (Johnson & Newport, 1989; Newport, 1990; Newport et al., 2001; Patkowski, 1990; Scovel, 1969), we would expect that tone language speakers should acquire AP for music most proficiently in early childhood, and that such proficiency should decline as age of onset of musical training increases, leveling off at around puberty. However, we would also expect the overall prevalence of AP to be higher among tone language speakers. In relation to this, we note that tone language speakers acquire the tones of a new tone language more easily than do speakers of nontone language—see Wayland and Guion (2004).

To examine the hypothesis that AP is more prevalent among speakers of tone language, Deutsch et al. (2006) undertook a large-scale direct-test study of two groups of music conservatory students. The first group consisted of 115 first-year students taking a required course at Eastman School of Music; these were all nontone language speakers. The second group consisted of 88 first-year students taking a required course at the Central Conservatory of Music in Beijing, China; these were all speakers of Mandarin. The students were tested in class, and there was no self-selection from among the subject population. Both the tone and nontone language speakers showed orderly effects of age of onset of training; however, the tone language speakers produced substantially higher scores than did the nontone language speakers, for all levels of age of onset of training.

In a further large-scale direct test study involving no self-selection of subjects, Deutsch et al. (2011) administered the same test of AP to 160 first- and second-year students at the Shanghai Conservatory of Music. Figure 4 plots the average percentage correct for each age-of-onset subgroup, and it can be seen that the level of performance here was very high. Those who had begun musical training at or before age 5 showed an average of 83% correct not allowing for semitone errors, and 90% correct allowing for semitone errors. Those who had begun training at ages 6–9 showed an average of 67% correct not allowing for semitone errors, and 77% correct allowing for semitone errors. Those who had begun training at age 10 or over showed an average of 23% correct not allowing for semitone errors, and 34% correct allowing for semitone errors.

Lee and Lee (2010) confirmed the high prevalence of AP among speakers of Mandarin in a direct test of 72 music students at National Taiwan Normal University, using a test similar in construction to that used by Deutsch et al. (2006), but employing three different timbres: piano, viola, and pure tone. Although they found the expected effect of age of onset of musical training, 72% of the subjects achieved overall an accuracy of 85% correct on the piano tones.

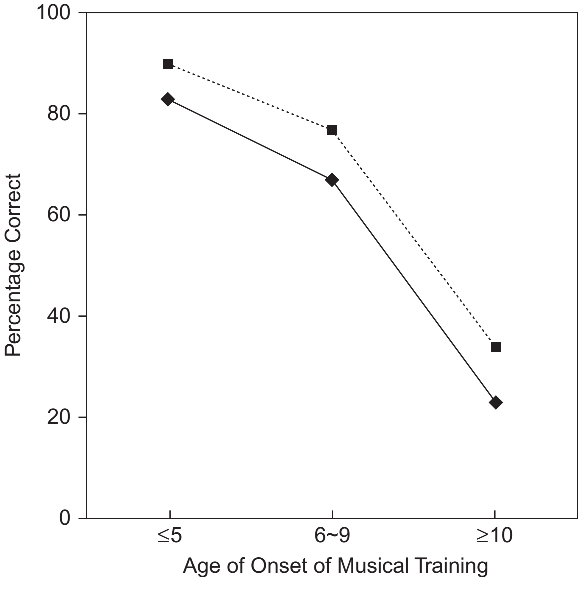


**Figure 4** Average percentage correct on a test of absolute pitch among students in a large-scale study at the Shanghai Conservatory of Music, as a function of age of onset of musical training. All subjects spoke the tone language Mandarin. Solid line shows performance not allowing for semitone errors, and dotted line shows performance allowing for semitone errors.
Data from Deutsch, Le, et al. (2011).

The findings of Deutsch et al. (2006, 2011) and of Lee and Lee (2010) are in accordance with the conjecture that the acquisition of AP is subject to a speech-related critical period, and that for tone language speakers, this process involves the same neural circuitry as is involved in acquiring the tones of a second tone language. However, the alternative hypothesis may also be considered that the prevalence differences between these groups were genetic in origin. To decide between these two explanations, Deutsch, Dooley, et al. (2009) carried out a direct-test study on 203 first- and second-year students at the University of Southern California Thornton School of Music, using the same AP test as had been used earlier, and again with no self-selection from among the target population.

The subjects were divided into four groups: Those in group *nontone* were Caucasian and spoke only nontone language. The remaining subjects were all of East Asian ethnic heritage, with both parents speaking an East Asian tone language. Those in the *tone very fluent* group reported that they spoke a tone language "very fluently." Those in the *tone fairly fluent* group reported that they spoke a tone language "fairly fluently." Those in the *tone nonfluent* group reported "I can understand the language, but don't speak it fluently."

Figure 5 shows the average percentage correct responses on the test of AP for each linguistic group. As before, there was a clear effect of age of onset of musical training. However, there was also an overwhelmingly strong effect of tone language fluency, holding ethnicity constant: Those subjects who spoke a tone language very fluently showed remarkably high performance—far higher than that of the Caucasian nontone language speakers, and also far higher than that of the East Asian subjects who did not speak a tone language fluently. The effect of language was even manifest in a fine-grained fashion: The performance of the *tone very fluent* group was significantly higher than that of each of the other groups taken separately; the performance of the *tone fairly fluent* group was significantly higher than that of the *nontone* group, and also higher than that of the *tone nonfluent* group. Further, the performance of the (genetically East Asian) *tone nonfluent* group did not differ significantly from that of the (genetically Caucasian) *nontone* group. In a regression analysis taking only subjects of East Asian ethnic heritage, fluency in speaking a tone language was found to be a highly significant predictor of performance.

The enhanced performance levels of the tone language speakers found in the studies of Deutsch et al. (2006, 2011), Deutsch, Dooley, et al. (2009), and Lee and Lee (2010) are consistent with the survey findings of Gregersen et al. (1999, 2001) from students in music programs of higher education in the United States referred to earlier. Gregersen et al. (2001) also found that the prevalence of AP among students who were Japanese or Korean was higher than among the Caucasian students, although not as high as among the Chinese students. As described in Section III,B, the high prevalence of AP among East Asian respondents to their survey was interpreted by Gregersen et al. to indicate a genetic origin for AP. However, in a reanalysis of their data, Henthorn and Deutsch (2007) showed that the prevalence of AP among students of East Asian descent with early childhood in North America did not differ from that of Caucasians, so that their findings cannot be attributed to ethnic differences.

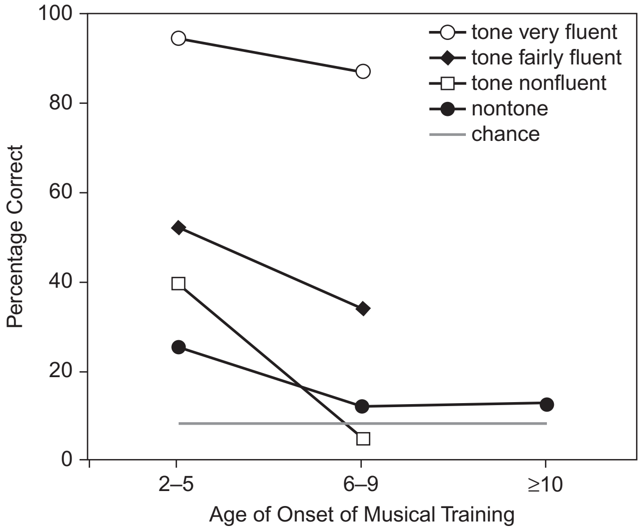


**Figure 5** Average percentage correct on a test of absolute pitch among students in a large-scale study at an American music conservatory. Data are plotted as a function of age of onset of musical training and fluency in speaking a tone language. Those in groups *tone very fluent*, *tone fairly fluent*, and *tone nonfluent* were all of East Asian ethnic heritage and spoke a tone language with differing degrees of fluency. Those in the *nontone* group were Caucasian and spoke only nontone language. The line labeled *chance* represents chance performance on the task.
Adapted from Deutsch, Dooley, et al. (2009).

Another point of interest in the study by Gregersen et al. is that the prevalence of AP was higher among the Chinese group than among the Japanese or Korean groups, and this prevalence in the latter groups was in turn higher than among the nontone language group. Japanese is a pitch accent language, so that the meanings of some words differ depending on the pitches of the syllables of which they are comprised. For example, in Tokyo Japanese the word “hashi” means “chopsticks” when it is pronounced high-low, “bridge” when it is pronounced low-high, and “edge” when the two syllables are the same in pitch. In Japanese, then, pitch also plays an important role in the attribution of lexical meaning; however, this role is not as critical as it is in tone languages. In Korea, some dialects are considered pitch accent or even tonal (Jun, Kim, Lee, & Jun, 2006). For example, in the Kyungsang dialect, the word “son” means “grandchild” or “loss” when spoken in a low tone, “hand” in a mid tone, and “guest” in a high tone. On the other hand, in Seoul Korean pitch is not used to convey lexical meaning. On these grounds, one would expect the overall prevalence of AP to be higher for speakers of Japanese and Korean than for speakers of nontone language, but not as high as for speakers of tone language. The survey findings of Gregersen et al. (1999, 2001) are as expected from this line of reasoning.

### E. Processing of Speech Sounds by AP Possessors

Evidence for enhanced processing of speech sounds has been found in AP possessors. In one experiment, Masataka (2011) required Japanese subjects to identify isolated syllables as rapidly as possible, and the mean response latency was found to be shorter for the AP possessors than for the nonpossessors. Because Japanese is a pitch accent language, this study left open the question of whether analogous findings would be obtained from speakers of nontone languages. However, Oechslin et al. (2010), in a study of German speakers, also found that AP possessors outperformed nonpossessors in tasks involving segmental speech processing.

## V. AP and Pitch Processing

It is often assumed that AP possessors have "good ears"—that is, that this ability is associated with enhanced low-level auditory abilities. However, experimental studies have not confirmed this view. For example, Sergeant (1969) and Siegel (1972) observed no difference between AP possessors and nonpossessors in their performance on frequency discrimination tasks. Fujisaki and Kashino (2002) confirmed the lack of difference between AP possessors and nonpossessors in frequency discrimination, and also found no difference between these two groups in the detection of tones in the presence of notched noise, in temporal gap discrimination, or in spatial resolution. On the other hand, AP possessors have been found to differ from nonpossessors in higher-level pitch processing, generally in advantageous ways. They exhibit categorical perception in note naming, while still discriminating between pitches within categories; they perform better on certain pitch memory tasks, on certain tasks involving the phonological processing of speech, and (except under unusual circumstances) in judging pitch relationships.

### A. Categorical Perception of Pitch

AP possessors automatically encode pitches into categories that correspond to note names, and such categorical perception has been explored in several experiments. For example, Siegel and Siegel (1977) presented AP possessors with tones whose pitches varied in 20-cent increments, and found that identification judgments reflected categorical perception in semitone steps. Miyazaki (1988) obtained similar findings, which are illustrated in the judgments of one AP possessor shown in Figure 6. However, more complex results have also been obtained. Burns and Campbell (1994) tested AP possessors on a pitch identification task employing tones that varied in 25-cent increments. The results varied across subjects; for example, the judgments of one subject showed consistent categorization in semitone steps, whereas those of another subject reflected the use of 25-cent categories. Both Miyazaki (1988) and Burns and Campbell (1994) observed that in contrast to

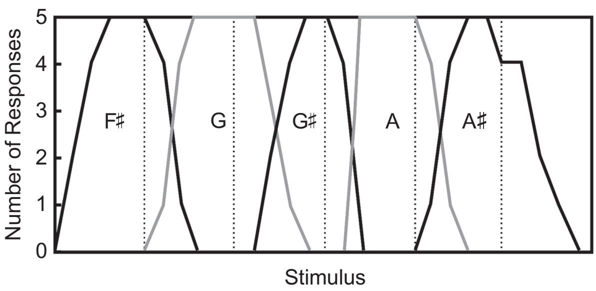


**Figure 6** Distribution of note naming responses by a single absolute pitch possessor, indicating categorical perception.
From Miyazaki (1988), with kind permission from Springer Science and Business Media.

categorical perception of speech sounds, for which discrimination functions are related to identification functions (Macmillan, Goldberg, & Braida, 1988), AP possessors discriminated between tones within categories while nevertheless exhibiting categorical perception in pitch identification tasks.

## B. Pitch Memory

The ability of AP possessors to categorize and encode pitches in verbal form confers a considerable advantage to pitch memory. In an early experiment, Bachem (1954) compared the performance of AP possessors and musically trained nonpossessors on a pitch memory task. A standard tone was presented, followed by a comparison tone, and the subjects indicated whether the tones were the same or different in pitch. The two groups showed roughly the same decay rate of pitch memory during the first minute. However at longer retention intervals, the performance of the nonpossessors continued to deteriorate, while that of the AP possessors remained stable—presumably because they were encoding the pitches in the form of verbal labels. Indeed, when AP possessors were able to label the tones to be remembered, they performed accurately with retention intervals as long as 1 week.

In a further study, Rakowski and Rogowski (2007) had subjects listen to a standard tone, and then tune a variable tone to match the pitch of the standard. When silent intervals of up to 1 minute were interposed between the tones, two AP possessors and a control nonpossessor exhibited very similar performance. However, beyond this period, the performance of the nonpossessor deteriorated with time, whereas that of the AP possessors remained more stable.

In a more elaborate experiment, Siegel (1974) used a paradigm similar to that of Deutsch (1970). Subjects were presented with a test tone that was followed by a sequence of intervening tones and then by a second test tone, and they judged whether the test tones were the same or different in pitch. When the difference between the tones to be compared was 1/10 semitone, the performance of the AP possessors and nonpossessors declined at roughly the same rate over a 5-sec retention interval. However, when this difference was 1 semitone, the performance of the two groups diverged substantially: that of the AP possessors remained stable at a high level, while that of the nonpossessors deteriorated sharply over a 15-sec retention interval. These results indicated that the raw memory trace characteristics of the two groups were similar, but that because the AP possessors adopted a verbal encoding strategy, they were able to draw on long-term memory in making their judgments when the pitch difference between the tones to be compared was roughly a semitone.

Following up on these findings, Ross and Marks (2009) suggested that children with minimal musical training who nevertheless show excellent short-term memory for pitch might be categorizing pitches in some way, and so might later develop AP as conventionally defined. The authors provided some preliminary evidence in favor of this hypothesis, and their intriguing suggestion awaits further investigation.

### C. Octave Errors

While the performance of AP possessors and nonpossessors in judging the octave placement of tones has not yet been compared, a number of studies have shown that AP possessors sometimes make errors in judging octave placement, while correctly identifying the note names (Bachem, 1955; Lockhead & Byrd, 1981; Miyazaki, 1989). However, octave errors are difficult to interpret. In contrast to the standard terminology for designating pitch classes (C C♯, D, and so on), there is no standard terminology for designating octaves. Subjects might therefore be unfamiliar with the octave terminology employed in any given experiment, and this could lead to artifactual errors. As another point, tones that are built on the same fundamental but played on different instruments (such as piano and harpsichord) can differ in perceived height, and so in perceived octave. In relation to this, the perceived height of a tone can also be made to differ substantially by manipulating the relative amplitudes of its odd and even harmonics (Deutsch, Dooley, & Henthorn, 2008; Patterson, 1990; Patterson, Milroy, & Allerhand, 1993). The octave designation of a tone of unfamiliar timbre can therefore be problematic in principle.

### D. Processing of Relative Pitch

AP possessors often feel uncomfortable when faced with arbitrarily transposed music, or when viewing a written score while simultaneously hearing the music played in a different key. This feeling of discomfort is understandable, because such listeners find the discrepancy between the notes they are viewing and hearing to be very salient. However, AP nonpossessors, who are often unaware of overall small pitch discrepancies, or at least regard them as fairly unimportant, sometimes find such a reaction puzzling, and may ascribe it to some cognitive or emotional problem. Indeed, because this reaction is often regarded as a sign of perceptual rigidity, several researchers have claimed that the AP possession confers a disadvantage to relative pitch processing—and even to musicianship in general (cf. Miyazaki, 2004). Given that many world-class musicians are AP possessors, this claim appears highly implausible at face value; however, the evidence for and against it is here reviewed.

Ward and Burns (1982) conjectured that the tendency for AP possessors to perceive pitches categorically might place them at a disadvantage in performing certain relative pitch tasks. Suppose, for example, that a listener were presented with $C_4 + 40$ cents, followed by $D\sharp_4 - 40$ cents. This produces an interval of 220 cents, and so should be recognized as a major second. However, an AP possessor might hypothetically perceive both the C and the D♯ categorically, and so identify the interval as a minor third instead. This conjecture was evaluated by Benguerel and Westdal (1991), who found that only 1 out of 10 AP possessors made errors in interval identification on this basis, and even then did not do so consistently. However, Miyazaki (1992) found that a minority of AP possessors made more errors in identifying detuned intervals when the first tone comprising the interval deviated from equal tempered tuning, so indicating a small effect in this direction.

Miyazaki (1993, 1995) further argued that AP possessors who were trained on a fixed-do system are subject to another source of error in making relative pitch judgments. He had subjects name intervals produced by tone pairs that were each preceded by a key-defining context (C, F♯, or a detuned E) created by a V7−I chord, with the first note of the pair being the tonic defined by the chord. The performance of AP possessors was degraded in the F♯ and detuned E contexts relative to the C context, and Miyazaki concluded that this was due to the influence on their judgments of a strong fixed-do template that was centered on C.

However, the task employed by Miyazaki (1993, 1995) was an unusual one. The subjects, who had been trained in the fixed-do system, were required to designate the intervals using solfège names (do, re, mi, etc.) relative to C. For example, in this experiment the correct answer for the interval F-A (a major third) was "mi"; however, the subjects had also been taught to use the label "mi" to designate the note E. Therefore for key contexts other than C, the subjects were for the most part required to designate an interval by using a note name (do, re, mi, etc.) that differed from that of either of the presented notes.

The unusual requirement to use solfège names to label intervals therefore produced a Stroop-like situation, so that AP possessors would be expected to experience confusion in performing this task. It was originally found by Stroop (1935) that when subjects were presented with the printed names of colors, their naming performance was impaired when there was a mismatch between the printed name and the color in which it was printed. An analogous effect was demonstrated by Zakay, Roziner, and Ben-Arzi (1984), who required AP possessors to identify the pitches of sung syllables, and found that their performance deteriorated when the syllables corresponded to the names of mismatched pitches. In a variant of this paradigm, Miyazaki (2004) reported that when a mismatch occurred between a syllable and the pitch in which it was sung, the pitch interfered with syllable naming for AP possessors. However AP nonpossessors, who would not have engaged in pitch naming in the first place, were not influenced by such a mismatch (see also Itoh et al., 2005).

Hsieh and Saberi (2008) provided further evidence confirming the involvement of a Stroop effect in judgments made by fixed-do trained subjects. These authors presented hybrid stimuli consisting of pitches that were voiced with solfège syllables. Subjects who had received fixed-do training (such as those studied by Miyazaki) showed substantial interference in pitch naming when the pitches and syllables were mismatched, whereas those who had received moveable-do training showed no such interference.

A further study on the issue of relative pitch processing by AP possessors was prompted by the general impression that such individuals often feel uncomfortable when viewing a written score while hearing the music played in a different key. Miyazaki and Rakowski (2002) carried out an experiment to determine whether the performance of AP possessors might be degraded by a conflict between mismatched auditory and visual stimuli. Subjects were presented with a standard melody that was presented in a written score, together with an aurally presented comparison melody. On some trials, the comparison melody was at the same pitch level as the standard, while on other trials it was transposed up or down. Further, on some trials, the pitch relationships formed by the standard and comparison melodies were identical, and on other trials they differed, and subjects judged whether the melodies were the same or different.

When the auditory and visual sequences were matched, the AP possessors outperformed the nonpossessors on this task; however, when the auditory sequences were transposed relative to the visual ones, the advantage to the AP possessors disappeared. In this latter condition, there was a marginal advantage to the AP nonpossessors, although this advantage became nonsignificant when the data of one anomalous borderline AP possessor was omitted. Yet the performance of the AP nonpossessors did not differ depending on whether the visually and aurally presented melodies were transposed relative to each other. Perhaps the AP possessors translated the visually presented notes into clearly imagined sounds, and this produced a conflict when they compared them with the transposed aurally presented melodies, whereas the nonpossessors viewed the written score in a more abstract fashion, so that no such conflict occurred. However, since the performance difference between the AP possessors and nonpossessors was only marginally significant, this issue awaits further investigation.

Given these findings, Miyazaki (2004) speculated more generally that AP possessors might have a general impairment in relative pitch processing, and even that "AP may be a disadvantage for musicianship" (p. 428). However, because these experiments were such as to engender Stroop-type conflicts on the part of AP possessors, the question arises as to how such listeners would perform under more standard, and ecologically valid, conditions.

Dooley and Deutsch (2010) addressed this question using a musical dictation task that was modeled after one used in the placement examination administered to first-year students in the University of Southern California Thornton School of Music. Thirty musically trained subjects were divided into three groups—AP possessors, borderline possessors, and nonpossessors—based on their performance on the AP test used by Deutsch et al. (2006) and Deutsch, Dooley, et al. (2009). All subjects were given a musical dictation task that consisted of three passages that they transcribed in musical notation. The starting note was furnished for each passage in order to provide a reference. There was a strong positive relationship between performance on the AP test and the musical dictation tasks, and neither age of onset of musical training nor years of training were significantly related to the dictation scores. The performance level was significantly higher for the AP possessors than for the nonpossessors, for the AP possessors than for the borderline possessors, and for the borderline possessors than for the nonpossessors.

In a further study, Dooley and Deutsch (2011) tested musically trained subjects consisting of 18 AP possessors and 18 nonpossessors, with the two groups matched for age and for age of onset and duration of musical training. The subjects performed interval-naming tasks that required only relative pitch. In contrast to the studies by Miyazaki (1993, 1995), the intervals were to be identified by their interval names ("major second," "minor third," and so on) so that no conflict was produced between the names that were used to designate the intervals and those of the notes forming the intervals. In one condition, the intervals were formed of brief sine waves that were just of sufficient duration to provide a clear sense of pitch (Hsieh & Saberi, 2007). In a second condition, piano tones were employed. A third condition was identical to the second, except that each interval was preceded by a V7–I cadence such that the first tone of the pair would be interpreted as the tonic.

Figure 7 shows, for each subject, the overall percentage correct in the interval-naming task. As can be seen, AP possession was strongly and positively correlated with interval identification performance. Further, the advantage to AP possession held under all conditions of interval presentation. It is of particular interest that the AP advantage was not erased by providing the interval to be named with a tonal context. So together with the findings of Dooley and Deutsch (2010) on musical dictation tasks,

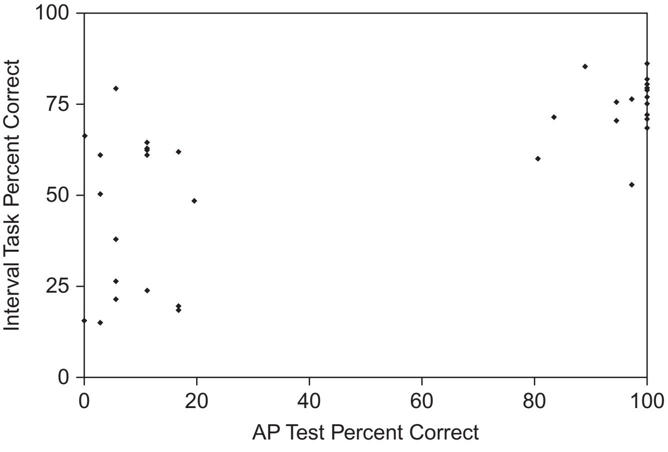


**Figure 7** Overall percentage correct on three interval naming tasks, plotted against percentage correct on a test for absolute pitch. A strong correlation emerged between absolute pitch possession and enhanced performance on the interval naming tasks. Adapted from Dooley and Deutsch (2011).

the findings from this experiment indicate that AP possession is strongly associated with enhanced performance on musical tasks requiring only relative pitch, given standard musical situations.

## VI. Neuroanatomical Substrates of AP

A considerable body of evidence has accumulated showing that AP is associated with unique brain circuitry, and this has implicated regions that are known to be involved in pitch perception and categorization, memory, and speech processing. The studies have involved both structural and functional neuroimaging (Bermudez & Zatorre, 2009b; Keenan et al., 2001; Loui et al., 2011; Oechslin et al., 2010; Ohnishi et al., 2001; Schlaug et al., 1995; Schulze et al., 2009; Wilson et al., 2009; Zatorre, 2003; Zatorre et al., 1998), and the obtained findings presumably reflect both innate factors, as well as environmental influences that operate during an early critical period.

One region that has been particularly implicated in AP is the left planum temporale (PT)—a region in the temporal lobe that corresponds to the core of Wernicke's area and that is essential to speech and language. The PT has been shown to be leftward asymmetric in most human brains (Geschwind & Levitsky, 1968), and in a seminal study, Schlaug et al. (1995) found that this asymmetry was exaggerated among AP possessors. Later, Zatorre et al. (1998) observed that the PT was larger in the left hemisphere among AP possessors than in a control group of subjects who were unselected for musical skill. Keenan et al. (2001) confirmed the exaggerated leftward asymmetry among AP possessors; however, in their study, this asymmetry was predominantly driven by a smaller right PT rather than a larger left one. Keenan et al. also found that the exaggerated leftward PT asymmetry did not occur in a control group of AP nonpossessors who had begun musical training at an early age.

Wilson et al. (2009) confirmed Keenan's findings and also reported that borderline AP possessors did not show the same exaggerated asymmetry—a finding consistent with the conjecture that this group should be considered neurologically distinct from high-performing AP possessors. In line with the structural findings, Ohnishi et al. (2001) observed that AP possessors showed enhanced activation in the left PT during passive listening to music, and Oechslin et al. (2010) found that AP possessors showed enhanced activation in the left PT and surrounding regions while performing a segmental speech processing task. Leftward asymmetry of the PT has been observed in the human fetus (Wada, Clarke, & Harem, 1975), so these findings can be taken to argue for a genetic—or at least innate—component to the predisposition to acquire AP.

Another region that has been implicated in AP is the left posterior dorsolateral frontal cortex. Zatorre et al. (1998) found that AP possessors showed enhanced activation in this region when covertly naming single tones, while nonpossessors showed activation in the same region when judging musical intervals. Taking into consideration other findings showing that this region is implicated in conditional associative learning (Petrides, 1985, 1990), Zatorre et al. hypothesized that AP possessors involve this region in the retrieval of associations between pitch values and their verbal labels (see also Bermudez & Zatorre, 2005). In line with these findings, Ohnishi et al. (2001) observed enhanced activation in the left posterior dorsolateral frontal cortex during a passive music listening task, and this correlated with high performance on an AP test.

Further differences between AP possessors and nonpossessors have been found by Schulze et al. (2009) employing a short-term pitch memory task similar to that developed by Deutsch (1970, 1975). In general, these authors found enhanced temporal lobe activity in both groups during the first 3 seconds following stimulus presentation, presumably reflecting stimulus encoding. They also found continued strong activity in the frontal and parietal cortex during the next 3 seconds, presumably reflecting activity in the working memory system. AP possessors showed greater activity in the left superior temporal sulcus during the early encoding phase, whereas the nonpossessors showed greater activity in right parietal areas during both phases. The authors hypothesized that brain activation among AP possessors during the early encoding phase involved the categorization of tones into pitch classes, with the result that they were able to place less reliance on working memory in making their judgments. In line with this reasoning, Wilson et al. (2009) found that borderline AP possessors recruited a more extensive neural network in performing a pitch naming task than did high-performing AP possessors, with the latter group instead showing activation particularly in the left posterior superior temporal gyrus.

The ability of AP possessors to place less reliance on working memory for pitch, owing to their enhanced ability to encode pitches in verbal form, could also account for their showing an absent or smaller P300 component of event-related potentials while performing pitch memory tasks (Hantz, Kreilick, Braveman, & Swartz, 1995; Hirose, Kubota, Kimura, Ohsawa, Yumoto, & Sakakihara, 2002; Klein, Coles, & Donchin, 1984; Wayman, Frisina, Walton, Hantz, & Crummer, 1992). This highlights the importance to AP of brain regions subserving pitch categorization discussed in Section V,A (Rakowski, 1993; Siegel, 1974; Siegel & Siegel, 1977). Interestingly, other studies have also associated the left superior temporal sulcus with sound identification and categorization (Liebenthal, Binder, Spitzer, Possing, & Medler, 2005; Möttönen et al., 2006).

An intriguing recent development concerns the role of connectivity between brain regions that are critically involved in AP. Loui et al. (2011), using diffusion tensor imaging and tractography, found that AP possession was associated with hyperconnectivity in bilateral superior temporal lobe structures. Specifically, they found that tract volumes connecting the posterior superior temporal gyrus and the posterior medial temporal gyrus were larger among AP possessors than among nonpossessors. These differences in tract volumes were particularly strong in the left hemisphere and survived control for onset and duration of musical training. When AP possessors were grouped into those with very high scores and those with lower scores, it was found that the more accurate AP possessors also had larger tract volumes in the left hemisphere.

# VII. AP Accuracy and Stimulus Characteristics

Among AP possessors, accuracy of note naming varies with the characteristics of the tones to be judged. Here we discuss effects of pitch class—including the advantage of white key notes over black key notes, the effect of the octave in which the tone is placed, and the effect of timbre.

## A. Pitch Class

AP possessors vary in the speed and accuracy with which they identify different pitch classes. In general, pitches that correspond to white keys on the keyboard—C, D, E, F, G, A, B—are identified more accurately and rapidly than those that correspond to black keys—C♯/D♭, D♯/E♭, F♯/G♭, G♯/A♭, A♯/B♭ (Athos et al., 2007; Baird, 1917; Bermudez & Zatorre, 2009a; Carroll, 1975; Deutsch et al., 2011; Marvin & Brinkman, 2000; Miyazaki, 1988, 1989, 1990; Sergeant, 1969; Takeuchi & Hulse, 1991, 1993).

Two main explanations have been suggested for the black/white key effect. Miyazaki (1989, 1990) argued that most AP possessors begin musical training on the piano during the critical period for AP acquisition, and that such training typically commences with simple five-finger patterns using only white keys, with black keys being gradually introduced as training proceeds. He therefore proposed that the white-key advantage for AP judgments results from piano practice with these notes during early childhood. In support of this argument, Miyazaki and Ogawa (2006) performed a cross-sectional study on children aged 4−10 who were taking keyboard lessons, and found that, overall, the children acquired the ability to name the pitches of notes in the order of their appearance in the lessons.

The hypothesis that the white-key advantage is due to early training on the piano was evaluated in the study by Deutsch et al. (2011). Here comparison was made between two groups of instrumentalists who began musical training at or before age 9. One group had begun training on the piano, and piano was currently their primary instrument; the other group had begun training on a non-keyboard instrument such as the violin, and they currently played a non-keyboard instrument. As shown in Figure 8, both groups showed a clear black/white key effect, and this was if anything stronger among those who were not keyboard performers. These findings argue that the black/white key effect cannot be attributed to early training on the white notes of the piano.

Another explanation for the black/white key effect was advanced by Takeuchi and Hulse (1991). These authors pointed out that, based on general observation, in Western tonal music white-key pitches occur more frequently than black-key pitches, and so should be better processed. This explanation in terms of frequency of occurrence is in line with findings showing that in other tasks, such as lexical decision making and word naming, responses are faster and more accurate to frequently occurring words than to words that occur less frequently (Besner & McCann, 1987). In accordance with this hypothesis, Simpson and Huron (1994) determined the

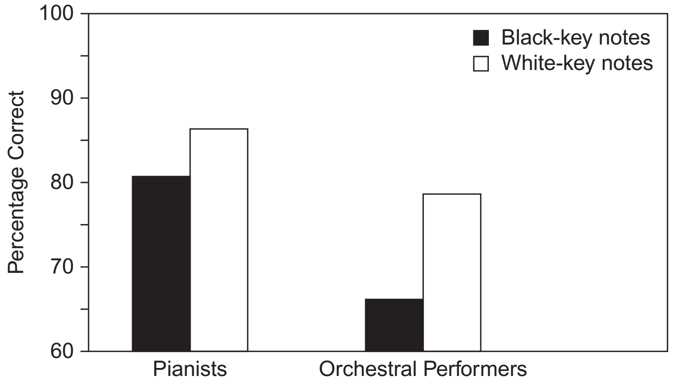


**Figure 8** Average percentage correct on a test of absolute pitch among students in a large scale study at the Shanghai Conservatory of Music, plotted separately for white-key and black-key pitches.
Data from Deutsch, Le, et al. (2011).

frequency of occurrence of the different pitch classes from a sample of works by Bach and Haydn, and found that this distribution correlated significantly with the distribution of reaction times obtained by Miyazaki (1989) from seven AP possessors. Huron (2006) proposed, in agreement with Takeuchi and Hulse, that the prevalence of AP for the different pitch classes might differ in association with their frequency of occurrence in the music to which the listener has been exposed.

In a large-scale analysis, Deutsch et al. (2011) plotted the percentage correct identifications of each pitch class, taking all 135 subjects in the study who had begun musical training at or before age nine. We correlated these percentages with the number of occurrences of each pitch class in Barlow and Morgenstern's *Electronic Dictionary of Musical Themes* (2008)—data kindly furnished us by David Huron. As shown in Figure 9, there was a highly significant correlation between note-naming accuracy and frequency of occurrence of the different pitch classes in this representative note collection. The result is particularly striking considering that the repertoire used in classes at the Shanghai Conservatory of Music, although having its primary input from Western tonal music, also has a larger input from Russian and Chinese music than occurs in Western music conservatories.

Another approach to the effect of pitch class was advanced by Athos et al. (2007) in the Web-based study described earlier. They observed an overall tendency for subjects to misidentify notes as a semitone sharp (for example, to misidentify the note D♯ as E). In particular, the note G♯ was frequently misidentified as A. Based on the latter finding, the authors proposed that since Concert A is used as the reference for orchestra tuning, pitch class A might serve as a "perceptual magnet" (Kuhl, 1991), so enlarging the perceptual region assumed by listeners to correspond to this note. However, according to their hypothesis, one would expect the note A to be

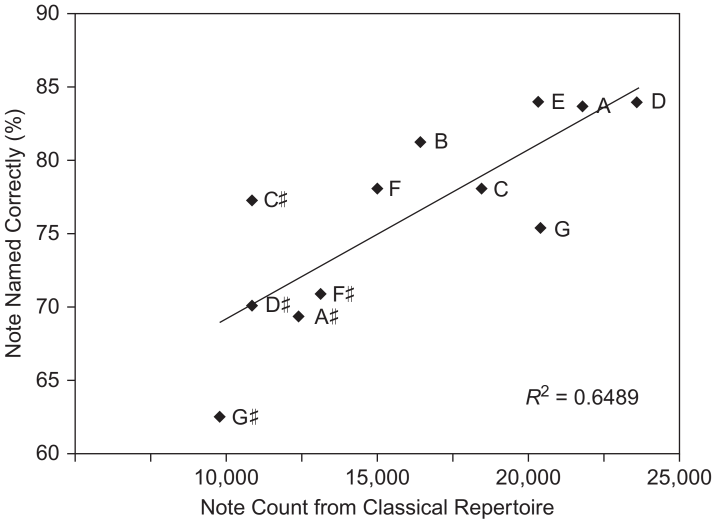


**Figure 9** Average percentage correct on a test of absolute pitch among students in a large scale study at the Shanghai Conservatory of Music, plotted for each pitch class separately, and against the number of occurrences of each pitch class in Barlow and Morgenstern's *Electronic Dictionary of Musical Themes* (2008).
From Deutsch, Le, et al. (2011).

most frequently identified correctly, yet Athos et al. did not obtain this finding. It appears, therefore, that the tendency to misidentify G♯ as A can best be ascribed to the general tendency to misidentify notes in the sharp direction. In a further investigation of this issue, Deutsch et al. (2011) confirmed the general tendency to misidentify notes as a semitone sharp; however no special status for the note A was found. Specifically, the probability of misidentifying G♯ as A was 7.9%, and of misidentifying G♯ as G was 6.17%. However, the probability of misidentifying A♯ as A was only 3.21%, whereas the probability of misidentifying A♯ as B was 12.59%. So the findings from this study run counter to the hypothesis that the note A acts as a perceptual magnet.

As a related issue, many musicians claim that they can identify a single reference pitch with ease—for example, Concert A in the case of violinists, and Middle C in the case of pianists (Bachem, 1955; Baggaley, 1974; Baird, 1917; Balzano, 1984; Revesz, 1953; Seashore, 1940; Takeuchi & Hulse, 1993). However, formal testing with notes presented in random order has not confirmed this view (Takeuchi, 1989; Deutsch et al., 2011), so this informal impression might have been obtained from judgments made in particular musical settings. The conditions under which AP nonpossessors might identify a reference pitch with accuracy remain to be identified.

## B. Octave Placement

A number of studies have shown that AP possessors name notes most accurately when they are in central pitch registers (Bachem, 1948; Baird, 1917; Miyazaki, 1989; Rakowski, 1978; Rakowski & Morawska-Bungeler, 1987). It is to be expected that note-naming accuracy would be reduced at the high and low extremes of the musical range, because the musical aspect of pitch is here lost (Burns, 1999; Lockhead & Byrd, 1981; Pressnitzer, Patterson, & Krumbholz, 2001; Semal & Demany, 1990; Takeuchi & Hulse, 1993). However, note-naming accuracy has been found to vary depending on register in the middle of the musical range also. Miyazaki (1989) presented notes that ranged over seven octaves and found that best performance occurred for notes between $C_4$ and $C_6$, with performance declining on both sides of this range, and declining more steeply on the lower side, as shown in Figure 10. A similar result was obtained by Deutsch et al. (2011) considering only notes in the middle three octaves ($C_3$-$B_5$). Performance at the lower octave was here significantly worse than at the middle or higher octave, while the difference between the middle and higher octaves was not significant. On general grounds, the effect of register might relate to the frequency of occurrence of the different notes in Western music, though this conjecture awaits formal investigation.

## C. Timbre

Although some AP possessors name pitches accurately regardless of how they are produced—for example, when they are produced by car horns, vacuum cleaners, air conditioners, and so on—others are accurate only for one or two instrument timbres with which they are familiar. Piano timbres appear to be particularly conducive to high levels of note naming (Athos et al., 2007; Baharloo et al., 1998; Lockhead &

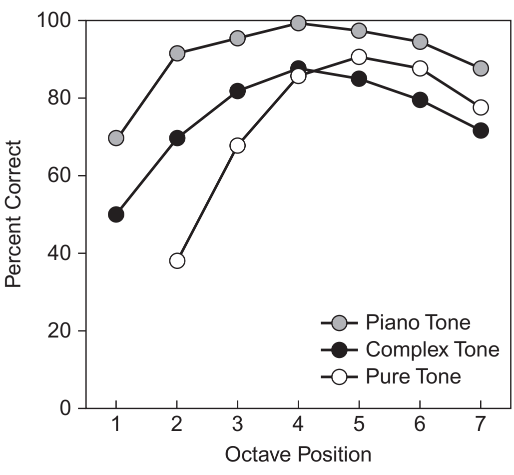


**Figure 10** Average percentage correct on a test of absolute pitch as a function of octave placement and instrument timbre. 1=$C_1$-$B_1$; 2=$C_2$-$B_2$; 3=$C_3$-$B_3$; 4=$C_4$-$B_4$; 5=$C_5$-$B_5$; 6=$C_6$-$B_6$; 7=$C_7$-$B_7$. From Miyazaki (1989). ©1989 Regents of the University of California.

Byrd, 1981; Rakowski & Morawska-Bungeler, 1987; Takeuchi & Hulse, 1993; Ward, 1999). For example, Lockhead and Byrd (1981) found that listeners who scored 99% correct on piano tones scored only 58% correct (69% discounting octave errors) on pure tones.

Miyazaki (1989) had seven AP possessors identify pure tones, complex "piano-like" tones, and piano tones. As shown in Figure 10, performance was most accurate for piano tones, less accurate for pianolike tones, and least accurate for pure tones. Further, in a large-scale study, Lee and Lee (2010) examined accuracy of note identification for synthesized piano, viola, and pure tones. They found a strong effect of timbre, with accuracy being highest for piano tones, lower for viola tones, and lowest for pure tones.

Sergeant (1969) demonstrated a more general involvement of timbre in AP. He recorded tones from a number of different instruments and spliced out their initial portions, so rendering their timbres unfamiliar. Pitch identification suffered for the truncated tones, and Sergeant argued that the important factor here was not the pattern of harmonics, but rather overall familiarity with perceived sound quality. AP decisions therefore do not only involve the processing of pitch values, but are derived from evaluating the note as a whole, taken as a bundle of attribute values. This argument is in line with the conjecture that AP originally evolved to subserve speech sounds, which occur as bundles of features, such as consonants and vowels.

## VIII. Pitch Shifts in AP Possessors

Although AP nonpossessors are able to detect pitch shifts of individual tones or groups of tones, with rare exceptions only AP possessors notice a shift of the entire tuning of the hearing mechanism. In particular, two sources of pitch shift have been identified—those occurring with advancing age and those associated with medication. These pitch shifts may well occur in the general population also, though AP nonpossessors might not be sensitive to them.

### A. Association with Advancing Age

Beginning as early as age 40–50, AP possessors generally find that pitches appear to be slightly sharper or flatter than they had been. People who have described such pitch shifts include J. F. Beck, who noticed at age 40 that he was beginning to hear notes a semitone sharp; this pitch shift progressed to two semitones at age 58, and to three semitones at age 71 (Ward, 1999). Also, P. E. Vernon (1977) observed that at age 52 he heard music a semitone "too sharp" and at age 71 as two semitones "too sharp." On the other hand, some AP possessors have noted that pitches appear flattened instead, and yet others do not appear to experience a pitch shift with age (Carpenter, 1951).

Athos et al. (2007), in their Web-based study, found that errors in pitch naming tended to increase with age, so that no subject in their study over 51 years of age identified all the tones in their test correctly. Such pitch shifts tended to be on the sharp side, though not consistently so. Athos et al. hypothesized that these pitch shifts could result from changes in the mechanical properties of the cochlea, though at present the physiological basis of this effect is unknown.

### *B. Association with Medication*

Concerning pitch shifts resulting from medication, carbamazepine—a drug that is widely used for the treatment of epilepsy and other disorders—has been the subject of particular interest. A number of studies have shown that this drug produces a downward pitch shift of roughly a semitone, though fortunately the effect disappears rapidly when the drug is discontinued (Chaloupka, Mitchell, & Muirhead, 1994; Fujimoto, Enomoto, Takano, & Nose, 2004; Konno, Yamazaki, Kudo, Abe, & Tohgi, 2003; Tateno, Sawada, Takahashi, & Hujiwara, 2006; Yoshikawa & Abe, 2003). AP nonpossessors who have taken carbamazepine sometimes state that the drug causes pitches to appear abnormal, and a few nonpossessors have been able to pinpoint the direction of the pitch shift as downward. In contrast, AP possessors can document the pitch shift with confidence; indeed, they often find the effect disconcerting, with one patient reporting that it produced "an unbearable sense of incongruity" (Konno et al., 2003).

Braun and Chaloupka (2005) carried out a detailed examination of the pitch shift under carbamazepine in a concert pianist. In a double-blind study involving all tones within a six-octave range, the subject shifted a mouse bar on a computer screen so as to match the visual representations of the presented tones with their perceived pitches in a fine-grained fashion. As shown in Figure 11, carbamazepine produced a downward pitch shift relative to placebo that was on average a little less than a semitone, with the extent of the shift increasing systematically from the lower to higher octaves. As another interesting finding, the black/white key effect persisted under carbamazepine. This applied to the pitches as they were perceived rather than to the tones as they were presented, indicating that the carbamazepine-induced effect occurs at a stage peripheral to that involved in the black/white key effect. Other than this, the neural basis of this pitch shift is unknown, though it has been hypothesized to be peripheral in origin (Braun & Chaloupka, 2005; Yoshikawa & Abe, 2003).

## IX. AP in Special Populations

The prevalence of AP is unusually high in certain rare populations. Interestingly, AP within these populations is associated with patterns of brain activation in response to sounds that differ from the patterns found among AP possessors within the general population.

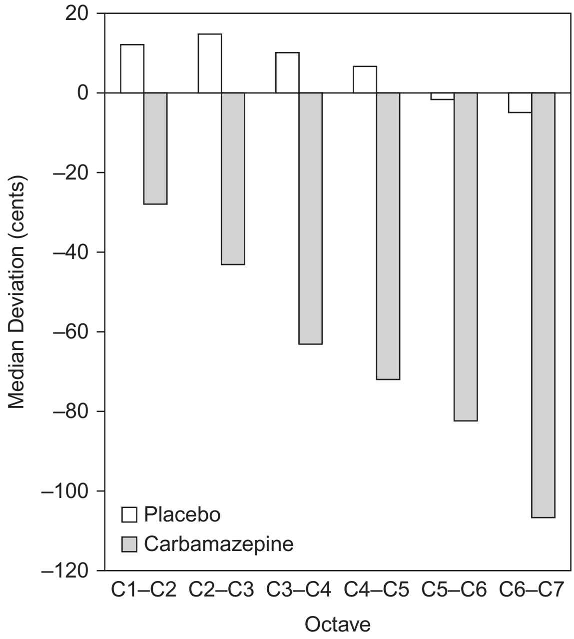


**Figure 11** Pitch shift induced by carbamazepine. The data show, for a single subject, the extent of the downward pitch shift induced by carbamazepine relative to placebo, as a function of the octave of the presented tone.
Adapted from Braun and Chaloupka (2005).

AP is highly prevalent among blind musicians—both those who are congenitally blind and those who have lost their vision very early in life (Bachem, 1940; Gaab, Schulze, Ozdemir, & Schlaug, 2006; Hamilton, Pascual-Leone, & Schlaug, 2004; Welch, 1988). For example, Hamilton et al. (2004) found that of 21 early blind subjects who were musically trained, 57% were AP possessors, some of whom had even begun taking music lessons in late childhood. The early blind, as a group, are also superior to sighted individuals in judging direction of pitch change, and in localizing sounds (Gougoux, Lepore, Lassonde, Voss, Zatorre, & Belin, 2004; Roder et al., 1999; Yabe & Kaga, 2005). It therefore appears that the high prevalence of AP in this group reflects a general shift in emphasis of brain resources from the visual to the auditory domain. Concerning neurological underpinnings, blind AP possessors have been found to produce more activation in non-auditory areas, such as visual and parietal areas, in performing pitch memory tasks (Ross, Olson & Gore, 2003; Gaab et al., 2006). In addition, Hamilton et al. (2004) observed a greater variability in PT asymmetry in early blind compared with sighted AP possessors.

There is also evidence that AP is more prevalent among autistic individuals. Autism is a rare neurodevelopmental disorder characterized by intellectual and communicative deficits that occur in combination with islands of specific enhanced abilities. Extreme forms of this syndrome exist in autistic savants, who show extraordinary discrepancies between general cognitive impairments and spectacular achievements in specific domains. Their prodigious talents are often musical. AP is highly prevalent among musical savants in association with other exceptional musical abilities, for example in composing, performing, improvising, and remembering large segments of music following very little exposure (Mottron, Peretz, Belleville, & Rouleau, 1999; Miller, 1989; Young & Nettlebeck, 1995).

Nonsavant autistic individuals often display a particular interest in music (Kanner, 1943; Rimland & Hill, 1984) and show substantially enhanced discrimination, categorization, and memory for the pitches of musical tones (Bonnel et al., 2003; Heaton, 2003, 2005, 2009; Heaton, Hermelin, & Pring, 1998) and speech samples (Järvinen-Pasley, Wallace, Ramus, Happe, & Heaton, 2008). It has been suggested that the superior categorization of sounds found in autistic individuals who lack musical training could indicate a predisposition to acquire AP (Heaton et al., 1998). As a caution, however, Heaton, Williams, Cummins, and Happe (2008) have pointed out that autistic persons who achieve discrepantly high scores on musical tasks might represent a specialized subgroup within the autistic population.

With respect to neurological underpinnings, although abnormal PT volumes occur in autistic persons, this pattern of asymmetry is quite unlike that in normal AP possessors (Rojas, Bawn, Benkers, Reite, & Rogers, 2002; Rojas, Camou, Reite, & Rogers, 2005). Rojas et al. (2002) in a magnetic resonance imaging study, found that PT volume was significantly reduced in the left hemisphere among a group of autistic adults compared with normal controls. However the two groups showed no difference in the right hemisphere, so that the autistic group essentially exhibited symmetry of the left and right PT. Later Rojas et al. (2005) confirmed this pattern in autistic children.

An enhanced prevalence of AP has also been hypothesized to exist among persons with Willliams syndrome. This is a rare neurodevelopmental disorder of genetic origin, characterized by mild to moderate intellectual deficits and distinctive facial features, together with other physiological abnormalities. Lenhoff, Perales, and Hickok (2001) found in an exploratory study that five individuals with Williams syndrome possessed AP, and they argued that this number was higher than might be expected; however, the relative incidence of AP among persons with Williams syndrome is at present unknown.

## X. Conclusion

Absolute pitch is an intriguing phenomenon that has long been the subject of considerable speculation and has recently drawn interest from researchers in a wide variety of disciplines, including music, psychology, neuroscience, and genetics. Although it had been considered an encapsulated ability, its study has contributed to the understanding of many issues, including critical periods in perceptual and cognitive development, relationships between language and music, the influence of language on perception, neuroanatomical correlates of specialized abilities, and the role of genetic factors in perception and cognition. The study of this ability should yield considerable dividends in the years to come.

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