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Markku Viitasaari

HOW TO DEAL WITH THE SYNTONIC COMMA IN MUSIC EDUCATION?

RECOGNITION, PREFERENCES OF USAGE, AND UTILITY

UNIVERSITY OF OULU GRADUATE SCHOOL;
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ACTA UNIVERSITATIS OULUENSIS
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MARKKU VIITASAARI

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Recognition, preferences of usage, and utility

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Abstract

This dissertation concerns interval intonation, tuning systems, and temperaments and their relevance to music education. It considers a historically well-known tuning discrepancy, the syntonic comma, from three different perspectives: 1) recognition, 2) preferences of usage, and 3) utility in music education. The first objective was investigating to what extent students in music-intensive classes and university music students are able to recognize a mistuning of the syntonic comma in musical passages tuned in just intonation. This was investigated through an experiment comprising 40 chord progressions. The second objective was to determine the preferences of university music students and teachers for dealing with the syntonic comma by way of centrally recognized tuning alternatives through an experiment with 30 pairs of chord progressions. The third objective was to consider how the present results and other recent research about the syntonic comma could help with teaching intonation skills. The Experiment 1, recognition of mistuning, revealed a wide distribution among listeners (n=168). The recognition of mistuning in vertical harmony decreased significantly according to the complexity of the chord progressions. Mistuning between successive notes of the melody line helped recognition. The recognition of mistuning was also influenced by the choir voice participants were repsenting: In one category of chord progressions, participants representing the bass voice in a choir detected mistuned triads better than participants representing the top voice. There was also a significant correlation of the mutually interrelated variables of instrumental experience and age with recognition of mistuning. In Experiment 2, intonation preferences, music university students and teachers (n=93) were asked a preference from among four tuning strategies with pairs of differently tuned but otherwise identical chord sequences. *Meantone tuning* (85.9%) and *equal temperament* (85.2%) were overwhelmingly preferred, with *local tempering* falling behind, and there was overall rejection of *pitch drift*. The results motivate the development of new exercises for intonation skills, and the experiments shed light on the problem of the syntonic comma, proving potential for practical music pedagogy. Several suggestions for further research are presented.

Keywords: consonance, dissonance, intonation, intonation systems, just intonation, meantone tuning, mistuning, pitch drift, pitch/frequency discrimination, pure intonation, pythagorean tuning, syntonic comma, temperament, tempering, tuning, well temperament

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Tiivistelmä

Tämä väitöskirja käsittelee intervallien intonaatiota, viritysjärjestelmiä, virityksiä ja niiden relevanssia musiikkikasvatuksessa. Työ keskittyy historiallisesti hyvin tunnettuun virityspoikkeamaan, syntoniseen kommaan kolmesta näkökulmasta: 1) tunnistamisesta, 2) käsittelyn mieltymyksistä ja 3) hyödyllisyydestä musiikkikasvatuksessa. Ensimmäisenä tavoitteena oli tutkia, missä määrin musiikkiluokkien oppilaat ja musiikin yliopisto-opiskelijat tunnistavat syntonisen komman puhdasvireisesti viritetyissä musiikkikatkelmissa. Tätä tutkittiin 40 sointusarjan kokeella. Toisena tavoitteena oli selvittää musiikin yliopisto-opiskelijoiden ja musiikin ammattilaisten mieltymyksiä erilaisiin syntonisen komman ratkaisutapoihin eli erilaisiin virityksiin 30 sointusarjaparin kokeella. Kolmantena tavoitteena oli selvittää, miten kokeiden tulosten ja tutkimuskirjallisuuden perusteella voisi edistää intonaatiotaitojen opettamista. Epävireisyyden tunnistamisen koe (1) paljasti laajan jakauman koehenkilöiden (*n*=168) kesken. Vertikaalisessa harmoniassa epävireisyyden tunnistaminen väheni merkittävästi harmonian kompleksisoitumisen myötä. Epävireisyys peräkkäisten sävelten välillä melodialinjassa auttoi epävireisen soinnun tunnistamista. Tunnistamiseen vaikutti myös se, mitä ääntä lauloi kuorossa: Yhdessä sointukategoriassa alinta ääntä laulavat osallistujat havaitsivat epävireisyyksiä paremmin kuin ylintä ääntä laulavat. Havaittiin myös merkittävä korrelaatio tunnistamisen sekä instrumenttiharrastuksen keston ja myös iän välillä. Intonaatiomieltymysten kokeessa (2) musiikin opiskelijoita ja opettajia pyydettiin valitsemaan identtisistä sointusarjapareista heille mieluisimman virityksen. *Keskisävelviritys* (85,9 %) ja *tasavireinen viritys* (85,2 %) koettiin selkäesti mieluisimmiksi, *paikallisen temperoinnin* jäädessä kolmanneksi. *Sävelkorkeuden ajautumaa* vierastettiin kauttaaltaan. Tulokset kannustavat kehittämään intonaatiotaitoja parantavia uusia harjoituksia ja kokeet valaisevat syntonisen komman ongelmaa osoittaen mahdollisuuksia musiikillisten käytäntöjen pedagogiikkaan. Diskussiossa esitetään useita jatkotutkimusehdotuksia.

Asiasanat: dissonanssi, epävireisyys, hyvä temperatuuri, intonaatio, keskisävelviritys, konsonanssi, paikallinen temperointi, puhdasvireinen viritys, pythagoralainen viritys, syntoninen komma, sävelkorkeuden ajautuma, sävelkorkeuden/frekvenssin erottelu, tasavireinen viritys, temperatuuri, temperointi, viritys, viritysjärjestelmä

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October 2020 Markku Viitasaari

Contents

1 Introduction

In this chapter, I will tell something about my personal musical background connected to this research. I also will introduce the basic knowledge about intonation issues in Sub-chapter 1.2. In addition, I will sketch the objectives and scope of this research in Sub-chapter 1.3. Dissertation structure is seen in Sub-chapter 1.4.

1.1 Researcher's path to the topic

I became interested in intonation issues as a university student when I was conducting different wind instrument groups of amateur players and music students. Later, while working as principal of the Panula College of Music in the Southern Ostrobothnia region in Finland, I had the opportunity to conduct elementary string ensembles and symphony orchestras. In addition, I have experience playing and singing in different groups. Intonation problems were often solved with vague instructions, like "listen to purity," or "listen to each other," or "your singing is mistuned." I noticed that a surprisingly common misunderstanding of intonation errors is that everything gets better if the out-of-tune tone is corrected in the sharp direction. A continuous stretching of intervals does not help the situation. I found out that many conductors of amateur groups completely ignore intonation errors. Such groups simply play pieces of music again and again without progress worth mentioning. A natural consequence of ignoring intonation is the lack of motivation—especially among young players. Accordingly, I became more and more interested in intonation problems and how to solve them. In brief, there were many intonation problems but few practical solutions.

These practical interests led me to write a study of intonation when I graduated from Helsinki Conservatory in 1999. The composer and lecturer of music theory Mauri Viitala guided me through the essential knowledge. As a master of ear training, the Conservatory's principal lecturer, DMA Timo von Creutlein, likewise put particular emphasis on intonation in ear training among students and required the same intensity from music graduates. I also came to understand that the requirement of pure or correct intonation can be used as an instrument of power, even arbitrarily.

Pitch-matching exercises, if realized without keyboard, are necessarily not locked into absolute pitches. Leading notes, for instance, can be intonated melodically as "high" but also clearly "lower" if followed by harmonic intonation.

A strong educator may misuse the power of expertise in working with an uncertain student with incomplete experience in intonation issues. This can happen both in ear training and instrumental lessons, meaning that it could be useful for music educators to be sensitive in this respect.

Gradually, when I became familiar with tuning systems and theories of intonation, I observed practical situations more carefully. I learned that brass sections are rewarding with respect to intonation training because small changes in tuning practices bring clear improvements that even amateur participants can aurally appreciate. String groups, conversely, may sound tolerable even when slightly poorly tuned. Tuning exercises in wind ensembles thus seem more productive than in string ensembles. Simple pitch matching to build chords helps enormously, especially if this kind of training is regular. At the same time, young players learn early that there is something that can be done to improve intonation.

The singing voice seems to be a world of its own. I have had countless frustrating discussions with classical singers regarding intonation in classical song performance. Perceptible tuning errors have only elicited mild comments about “small technical problems.” Perhaps “the tempo was too slow,” but nevertheless, “she has a superior quality of voice.” Over time, I have learned to remain silent.

I continued this topic in my licentiate thesis, supervised by PhD, PhLic (Education) Professor Matti Vainio at the University of Jyväskylä in 2001. The subject of that thesis was *Yksi vai useampi intonaatio [One intonation or several intonations]*, for which I investigated the methodology of teaching intonation based on historical style periods of Western music. This study revealed that there are plenty of methods to extend awareness of intonation in the Western tradition on the basis of style periods. I described several harmonic progressions and analyzed them on the basis of Pythagorean tuning, just intonation, and extended just intonation, applying these analyses to ear training. The empirical part of the study showed that intonation issues were almost ignored in current Finnish learning materials on ear training (Viitasaari, 2001, pp. 76–78, 133–134).

After publishing my licentiate thesis, the deeper investigation of intonation issues continued bothering me, and I became a doctoral student of musicology at the University of Turku in 2003. Unfortunately, I had to interrupt these studies, but my lifetime interest in intonation issues persisted. However, PhD, MSoc.Sc. Erkki Huovinen supervised my work for a couple of years, and several ideas were developed. The basis of the chord progressions used in this research was planned at that time.

1.2 Background

When children learn to play an instrument with non-fixed tuning (string instruments and wind instruments), they first must learn how to produce a sound from the instrument. Quite soon, they have to somehow learn to adjust the pitch. Usually, young instrumentalists learn this adjustment close to the fixed pitches of *equal temperament* —often in reference to the piano or a keyboard. When young players play together in an ensemble or orchestra, they have to adjust the pitch without a fixed reference system. According to Leedy and Haynes (2005, p. 503) intonation can be defined as an acoustically and artistically correct pitch of the tone played by a musician or sung by a singer. In other words, accurate pitch matching belongs to intonation. The concept of intonation is discussed in Sub-chapter 2.1.1.

Musical intervals are defined by pitch differences, and melodies are formed using pitch variations over time (Micheyl, Delhommeau, Perrot & Oxenham, 2006, p. 36). Thus, pitch perception is considered an essential ability for a musician (Geringer, MacLeod, Madsen & Napoles, 2015, p. 675). Indeed, playing in tune is an ability that musicians distinctly emphasize (Geringer, MacLeod & Sasanfar, 2015, p. 90). For musicians or singers to perform in tune, they must have the ability to accurately perceive pitch in the surrounding music and in their own performance. In-tuneness can be understood as proper intonation, and out-of-tuneness can be understood as poor intonation. What exactly is meant by "poor" intonation or being "out of tune" demands more analytical work. For instance, a performance can be said to have poor intonation when it includes some mistuned chords. The melody can be mistuned, yet the accompaniment sounds correct. Musical performances can be experienced as being in tune or out of tune. One problem with this dichotomy is determining the correct reference system, and the question of in-tuneness and out-of-tuneness is contextual; there are numerous tuning systems. It is also a question of artistic interpretation, such as when, for example, the singer of, say, an opera aria performing with a symphony orchestra may, in relation to the orchestra, use ambiguous intervals that someone could judge as being out of tune.

If musicians play with a piano or keyboard accompaniment, it seems natural that the "right" pitch will be the equal temperament. But in a different circumstance, such as an *a cappella* choir singing a piece from the Renaissance, there are possibilities for *just intonation* intervals, which deviate from equally tempered pitches. Hence, mistuned intervals in such cases might be evaluated in relation to just intonation, not to equal temperament. Further, if an a cappella group sings medieval *organa*, they possibly aim at *Pythagorean tuning* (introduced in Sub-chapter 2.1.4), where the scale is built of successive perfect fifths, and it contains large major thirds. In this context, the major third of just intonation, for instance, is mistuned in relation to the Pythagorean tuning.

Most music listeners can understand that all kinds of music can be played with piano or keyboard accompaniment: a child playing the violin, a popular artist singing, and a professional opera singer performing. We hear J. S. Bach's fugues and contemporary music played on the piano, and the instrument is used for choir accompaniment as well. Everything seems to work straightforwardly with piano accompaniment. Modern piano is equally tempered, which means (in the Western tradition) that an octave interval is divided into 12 equal subdivisions (Renney, Gaster & Mitchell, 2018, p. 2). Johnson-Laird, Kang, and Leong (2012, p. 32) claim that very few people have the possibility of hearing music any tuning other than equal temperament in their lifetime. If one listens to industrially produced pop music and does not experience concert situations with choirs or acoustic ensembles, this may be true.

On the basis of ordinary observations, the teaching of musical instruments seems to be steeped in equal temperament, independent of context. Students practice their melodic instruments alone or with piano accompaniment. Players of orchestral instruments—percussion, string, and wind instruments—practice with a pianist. This is pedagogically understandable and even mostly prudent in many situations. However, if the only approach is equal temperament, it may be challenging to achieve more sophisticated pitch adjustments in the tonal music repertoire. To simplify, pitch matching as a part of non-fixed intonation is a more complicated skill than matching the pitch with the modern piano. Jeans (1937, p. 184) remarked that due to equal temperament, the music of, say, Bach and Handel, is not heard tonally as it was intended to be heard. Ryan (2016, p. 34) suggested that the equal division of the octave is an oversimplification that conceals the mathematical scope of frequency from the musician. Bohrer (2002, p. 50) argued that equal temperament has been the absolute ruler over intonation. It is quite challenging to learn to intonate in just tuning (i.e., just intonation, presented in Subchapter 2.1.4) without the experience of hearing just intonation chords and intervals. According to Kopiez (2003, p. 404), the use of equally tempered piano in the early phase of instrumental teaching may cause a sort of burn-in effect in intonational behavior.

At a time when intonation was more flexible, musicians, and even audiences, may have been more aware of temperament's transient nature. There has been a long-standing misunderstanding that a fixed model of intonation should be the guideline of intonation (Bohrer, 2002, p. 50). Duffin (2008, p. 159) puts it clearly: "ET [equal temperament] is not necessarily the best temperament for every single musical situation encountered by today's musicians."

However, the dominance of equal temperament in the Western tradition is quite new in music history. The equal temperament, the way we tune modern pianos and keyboards, was not adopted on a large scale until the middle of the 19th century. Moreover, Duffin (2007) and Jeans (1937, p. 175) note that the acceptance of equal temperament was not a quick process. Starting around 1850, it gradually became more common to tune pianofortes and pianos in equal temperament. After that, tuning organs in equal temperament became more common with new instruments, but old organs were still tuned to the meantone temperament for decades. Duffin (2008) thinks that William Braid White's book *Modern Piano Tuning and Allied Arts* can be considered a kind of turning point in the generalization of equal temperament (Duffin, 2008, pp. 106–115).

For modern people, equal temperament is an understandable and easy approach to Western music, independent of context and century. It provides approximate values that are useful as a referential system. It is tempting to resort to the piano and keyboards in sight singing, choral training, and ensembles of young players. Aiming toward optimal intonation can begin with equal temperament, but in most cases, it can be improved by familiarizing oneself with more profound intonation issues and the history of tunings and temperaments. Awareness of historical keyboard temperaments and tuning systems and fine accurate adjustment of musical intonation could perhaps be more widespread, at least for music education and the training of music professionals. As Bohrer (2002, p. 43) notes, a huge number of keyboard temperaments have been proposed during the past centuries, and this richness could be easily put to use with electric keyboard instruments. In particular, several temperaments were developed for keyboards during the baroque period (Reinhard, 2016, p. 3), and the repertoire of the baroque period is in common use; why not use the temperaments made for this music?

All this generates questions: Why are there so many different temperaments in the history of Western music? What about music without keyboards? What should a conductor do to improve intonation in an amateur choir? What should the conductor of a junior wind band do to improve intonation? One possible answer is simple at the level of understanding the history of intonation systems—especially the principle of "just intonation." This tuning system, which uses intervals corresponding to simple integer ratios (Renney et al. 2018, p. 2), is presented in more detail in Sub-chapter 2.1.5. The problem of the so-called *syntonic comma* (also presented in more detail in Sub-chapter 2.1.5) becomes visible when those small-integer ratios are used to create the Western scale on a fixed tuning instrument, like the piano (Sponsler, 2011). Basically, the syntonic comma appears as a conflict between the major third and the perfect fifth. Practical solutions for intonation problems are called *temperaments, and they are the* focus of Sub-chapters 2.1.4, 2.1.5, 2.1.6, and 2.1.7.

According to Stange, Wick, and Hinrichsen (2018), attention to historical performance practices, just intonation, and other non-equally tempered ways of tuning increased during the second half of the 20th century. From this perspective, equal temperament can be seen as an intermediate step rather than a final solution to intonation issues. The development of digital media further improves the dialogue between different music cultures and intonation systems (Stange et al. 2018, pp. 58–59).

1.3 Objectives and scope

The concepts of "just intonation" and "syntonic comma" are in focus in this dissertation, along with the notions of "pitch perception," "pitch discrimination," "temperament," and "tuning." The research literature on these issues may seem complicated and theoretical from the music learner's point of view. This includes the central tuning theoretical notion of the syntonic comma—a fundamental discrepancy between pure perfect fifths and pure major thirds and that is thus involved in most commonly used tuning systems and temperaments. Interestingly, musicians must implicitly find solutions to the problem of the syntonic comma in ordinary musical performances.

Thus, the *overall objective* of this work is to address the relevance of the syntonic comma in music education. Do young musicians recognize the comma at all? If so, what factors influence such recognition? Do they prefer any of the theoretical solutions proposed for dealing with this problem? If they do, could this information somehow be useful for music education?

First, then, we may ask whether and to what extent the fine distinctions of tuning described in the theoretical literature are perceptible to musicians and music listeners. Here, my purpose is to clarify to what extent young music learners recognize the syntonic comma in certain contexts and what factors influence that recognition. On the one hand, there are reasons to assume that the harmonic context of musical material could influence recognition. It might be, for instance, that fine mistunings are mostly recognizable only in very simple tonal contexts. On the other hand, aspects of musical experiences might also affect listeners' sensitivity to tuning. By mistuning, I am referring to the differences and distinctions of one solution to the comma problem in comparison to other such solutions.

Further, I am interested in more advanced music students' sensitivity to different tuning and temperament alternatives. In particular, I will address whether musically educated listeners find certain methods of dealing with the syntonic comma more preferable than others. As will be seen in Chapter 2, different style periods of Western music have provided a large number of tuning alternatives to equal temperament. It is worth exploring which tuning solutions sound best to musicians' ears. There are justifiable reasons to assume that equal temperament has numbed musicians' sensitivity to different intonation adjustments. If this assumption is shown to be correct, there may be clear pedagogical challenges to revive the sense of fine adjustments in intonation. Conversely, if music students and music professionals also accept the sounds of tuning methods other than equal temperament, that alone might offer an interesting basis for efforts to broaden their consciousness of intonation issues.

Finally, we may also ask how the various usages of the syntonic comma could play helpful roles in teaching intonation skills. Following the two empirical experiments of this work, I will be able to address any potential pedagogical implications of the results. In this context, previous research regarding intonation issues in musical performance may be interpreted from a pedagogical point of view. As a whole, the dissertation thus aims to strengthen the pedagogy of intonation issues in music education.

1.4 Dissertation structure

This dissertation consists of five chapters and a broad list of appendices. In Chapter 1, I have outlined the context for the research agenda. The key concepts of intonation are introduced in Sub-chapter 2.1. The literature review laying the foundation for Experiment 1 (recognition of mistuning) is introduced in Sub-chapter 2.2, separately from the literature review for the experiment of intonation preferences presented in Sub-chapter 2.3. The literature review for pedagogical motivations is presented in Sub-chapter 2.4. The research questions (see Sub-chapter 2.5) are presented next, and a short description of the study's processes then ends Chapter 2.

Because of the unique research design, the introduction of experiments requires a rather large amount of space. The main findings of Experiment 1 (recognition of mistuning) are presented in Chapter 3, Sub-chapter 3.3, and the main findings of Experiment 2 (intonation preferences) follow, in Chapter 4, Sub-chapter 4.3.

The discussion in Chapter 5 answers the research questions (see Sub-chapter 5.1) and discusses the practical implications of this study's results (see Sub-chapters 5.2, 5.3, and 5.4). Critical observations from the present work are discussed in Sub-chapter 5.7. Finally, recommendations for further research are presented in Sub-chapter 5.8. A broad methodological list of appendices is necessary because of the unique musical material of these experiments.

2 Theoretical framework

In this chapter, I will introduce the key concepts (see Sub-chapter 2.1) of theoretical framework concerning intonation issues: There will be eight sub-chapters (2.1.1–2.1.8) clarifying the vast richness of historical tunings and temperaments. Sub-chapter 2.2 creates an overview to previous research of recognition of mistuning. Sub-chapter 2.3 includes an overview to previous research of intonation preferences. These sub-chapters are connected to two experiments of this research. In addition, there will be a short review without a separate experiment: Pedagogical motivations are presented in Sub-chapter 2.4. The research questions are written in Sub-chapter 2.5. The last sub-chapter includes a short description of the study's processes.

2.1 Key concepts

The issues of intonation have long inspired researchers, and music theorists and musicians have been interested in the problems of tuning musical instruments since ancient Greece. Numerous temperaments have been developed, mainly for keyboards, during the different style periods of Western music. This richness of tuning systems flourished until the 19th century, but the last 150 years have been more or less dominated by equal temperament. In particular, the electric context of popular music has adopted it without question. In ordinary observations, it seems that the mainstream of education in music theory and ear training has been satisfied with the viewpoint of equal temperament. It would not be difficult to argue that something has been lost. During the last few decades, numerous composers of contemporary music have rediscovered the diversity of tuning systems, which might also be fruitful in the context of music education.

2.1.1 Tuning, temperament, and intonation

> The tuning of musical instruments has kept music theorists busy since antiquity. It is a *[sic]* commonplace—although no less true for that—to say that each period in the history of music has had its own theory of tuning in order to meet its own musical needs. (Rasch, 2002, p. 193)

This quote describes well the vast breadth of intonation systems. It would be fascinating to chart out the immense richness of historical tuning systems and temperaments. However, only the essential key concepts will be introduced in this chapter. This work focuses on the syntonic comma and its occurrence in practical situations related to music education.

Villegas and Cohen (2010) defined the concepts of intonation and tuning, saying, “Tuning refers to the frequency specification of an entire set of tones available for a given instrument” (p. 78). Villegas and Cohen (2010) argue that a tuning system determines the gamut of available tones that can be used for constructing scales and modes. Tuning systems mostly involve a repetition factor—the octave is a representative example. Hence, it also defines a number of divisions between repetition factors, for example, pitch classes or chroma, generally 12 divisions per octave (Villegas & Cohen, 2010, pp. 78–79).

Sponsler (2011, p. 7) described temperaments, or “systems of incorporating the comma into the scale in various intervals.” Various temperaments are introduced in the following sub-chapters. Villegas and Cohen (2010, p. 79) define the concept of temperament in music: “Temperament is a technique in which pure intervals are altered to satisfy other requirements, such as distributing a comma (an interval smaller than a semitone resulting from dividing the octave according to small integer numbers).” The syntonic comma is examined more closely in Sub-chapter 2.1.5. Bohrer (2002) argues that the syntonic comma is the main goal of the procedures designed to realize temperaments, and it thus has spread out in a variety of ways in all temperaments. These systems are called closed temperaments. In this approach, the term ”tuning system” implies openness in that the number of notes in the system may be extended by employing higher integers in the just frequency ratios of the intervals. By contrast, ”temperaments” are closed systems in which the number of notes is constrained by intonational adjustments (Bohrer, 2002, pp. 42–43). This distinction of Bohrer’s is interesting, but it has not been generally adopted in the literature.

Intonation as a multilateral concept

In-tuneness is a central concept in many definitions of intonation. Yarbrough, Karrick, and Morrison (1995, p. 32) define intonation as the “ability to perform in tune.” According to Kopiez (2003), intonation “refers to skillful ability of playing in tune” (p. 384). Leedy and Haynes (2005, p. 503) argue that intonation is often understood in a narrow way: the acoustically and artistically correct pitch of the tone played by a musician or sung by a singer. In the present study, this aspect of intonation (playing in tune) is examined on the basis of recent research.

According to Karrick (1998), the term “intonation” can denote the results of tuning or the level to which players achieve in-tuneness (1998, p. 112). Morrison and Fyk (2002) emphasize the viewpoint of audience: “To many listeners, in-tuneness might be a more global assessment of musical quality thanks to just pitch precision” (p. 185). Indeed, audiences deserve well-intonated performances.

Geringer and Worthy (1999, p. 135) point out the pedagogical aspect of in-tuneness: ”Learning to play in tune is of paramount importance in instrumental music education.” According to Yarbrough et al. (1995, p. 232), intonation is one of the primary aspects in the evaluation of both ensemble and solo performances. Cuffman (2016, p. 73) refers to the complexity of intonation, saying, “Learning to play in tune together is an endless process.” This is a definition with truth—the improvement of intonation never ends. Indeed, Scholtz (1998) thinks that the solution to intonation problems lies only in dynamic “ad hoc adjustments of pitch.” These adjustments help to obtain optimal consonance, but also preserve the melodic line and pitch stability (Scholtz, 1998, p. 10).

Bohrer (2002) has defined two separate principles for intonation. In the case of fixed pitch instruments, the reference note of a scale, temperament, or tuning system is expected to remain unchanged. Bohrer calls this the *fixed frequency principle*. In the case of instruments with flexible intonation and the singing voice, the necessity or value of complying with a reference frequency is not apparent at all. In Bohrer’s terminology, this principle is called the *flexible reference principle* (Bohrer, 2002, p. 52). These concepts may not have been widely adopted in the literature, but they are understandable and logical, and they provide a useful starting point for thinking about performers’ solutions for intonation.

Morrison and Fyk (2002) suggest that intonation consists of several sub-skills, which are pitch discrimination, pitch matching, and instrument tuning. Pitch discrimination is a listener’s ability to perceive simultaneous pitches (chords) and successive pitches (melodies). Pitch matching is a kind of active sound shaping, and it is a separate skill from manipulating pitches. It is unclear whether instructions improve intonation skills. It is also not clear enough whether even experience improves intonation skills. Pitch-matching accuracy seems to improve with training (Morrison & Fyk, 2002, pp. 187–190). However, from the present study’s point of view, pitch discrimination is an essential skill. Experiment 1 (recognition of mistuning) is strongly related to this aspect of intonation.

Morrison (2000) defines the concept of good intonation as “the ability to adjust performed pitches to minimize or eliminate perceived discrepancies” (p. 40). This is, according to Morrison, a kind of amalgam of many abilities that have been developed over time, and the progressive interaction of these abilities underlies high-level musical achievements (2000, p. 40). Eliminating perceived discrepancies resonates very well with the present study—the tuning alternatives used in Experiment 2 are solutions to the problem of the syntonic comma. Some researchers bring the multidimensionality of intonation to the fore. According to Leedy and Haynes (2005, p. 503), intonation has remarkable significance for the musical expression of various styles and for their meaningful features, such as tension and release and the coloring of melodies. Kanno (2003) largely agrees with them: “Pitch is always related to other musical elements such as tone color, register, dynamics and articulation” (p. 42). Intonation is one way to make musical timbre perceptual—which is something music notation does not convey (Kanno, 2003, p. 48). From this perspective, intonation also covers aesthetic aspects that go beyond such skills as Morrison and Fyk’s pitch discrimination, pitch matching, and instrument tuning. In this vein, Kopiez (2003) notes: “The perception of mistuning of varying degrees is not simply a question of psychoacoustics but also has a considerable influence upon aesthetic appreciation” (pp. 384–385). Appreciating intonation as an aesthetic experience is relevant for Experiment 2 (intonation preferences), where different tuning alternatives are compared in a holistic fashion.

2.1.2 Harmonic series

Singers and instrumentalists produce harmonic tones that include, above and beyond the fundamental frequency, an overtone series of frequencies based on simple integer (whole number) ratios. The tuning of intervals can be derived from the distances of these so-called harmonics or harmonic partials. The basics of different tuning systems like Pythagorean tuning and 5-limit just intonation can thus be deduced from the harmonic series (see, e.g., Devaney 2011, pp. 10–11).

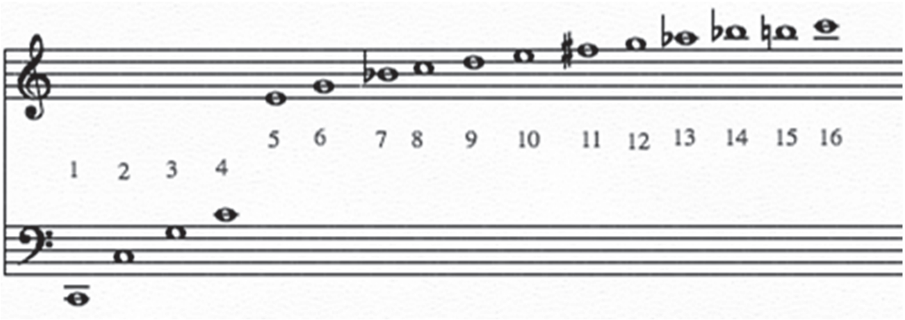

Fig. 1. The harmonic series presented in musical notation. The ordinals of the harmonic partials can be used to indicate frequency ratios corresponding to the intervals formed within the harmonic series.

Musical intervals can be determined straight from the harmonic spectrum. The intervallic distance between the first and second partials constitutes an octave and corresponds, in the physical domain, to the frequency ratio 2:1. The distance between the second and third partials constitutes a perfect fifth (3:2), while the third and fourth partials constitute a perfect fourth (4:3). Similarly, the fourth and fifth partials make up a major third (5:4), and the fifth and sixth partials constitute a minor third (6:5). This list could be continued with ever smaller intervals.

Intervals can be calculated and “piled” very easily using the ratios inherent in the harmonic series. Piling requires the multiplication of ratios. Let us take the pure fifth and the pure fourth. Adding these two intervals should yield the perfect octave. This corresponds to the following multiplication of frequency ratios:

$$3:2 \times 4:3 = 12:6 = 2:1$$

Similarly, adding the intervals of a major third and a minor third gives the perfect fifth:

$$5:4 \times 6:5 = 30:20 = 3:2$$

Likewise, a minor second and a major third produce the perfect fourth:

$$16:15 \times 5:4 = 80:60 = 4:3$$

A pure fifth and a major third give the major seventh:

$$3:2 \times 5:4 = 15:8$$

As a final example, consider adding a pure fourth and a major third, resulting in the major sixth:

$$4:3 \times 5:4 = 20:12 = 5:3$$

In this research, intervals are usually presented both as ratios (2:1, 3:2) and as cents. The octave is 1200 cents, and in equal temperament, the semitone is 100 cents, the whole tone 200 cents, and so on. When an interval with a simple integer ratio is transformed into cents, the following formula is used:

$$\log2(f2/f1) \times 1200 \approx 3986 \times \log10(f2/f1)$$

(cf. Gordon, 1983, p. 24; Sethares, 2005, p. 317). Tunings and temperaments are introduced in Sub-chapters 2.1.4, 2.1.5, and 2.1.6.

2.1.3 Consonance and dissonance

Harmony is a fundamental feature of Western tonal music that consists of simultaneous pitch combinations. These pitch connections are traditionally classified as either consonant or dissonant. Musical consonance and dissonance have thus been widely discussed in musical and acoustic theory (Backus, 1977; Parncutt & Hair, 2011; Partch, 1974; Rameau, 1722/1971; Schoenberg, 1911/1978; Schön, Regnault, Ystad & Besson, 2005; Tenney, 1988; Terhardt, 1984; Von Helmholtz, 1912).

The use of these concepts has also evolved through music history, from the Ars Antiqua to the 20th century (see Tenney, 1988). Consonant intervals are usually associated with pleasantness and dissonant ones with unpleasantness, and it is often thought that consonance is somehow fundamental and primary (see, e.g., Schenker, 1935/1979). Despite centuries of discussion and theories concerning pitch relationships, it seems that certain claims regarding intervallic consonance remain stable. Behavioral evidence shows, time and again, that, for example, an octave (2:1) or a perfect fifth (3:2) are perceived as more pleasant (consonant) than intervals with more complex ratios (see, e.g., Schön et al., 2005).

It has thus been common for scholars in this field to make strict categorizations of intervals into consonant and dissonant classes. A typical distinction is the one made between *perfect consonances* (unison, perfect fourth, perfect fifth, and perfect octave), *imperfect consonances* (minor third, major third, minor sixth, and major sixth), and *dissonances* (minor second, major second, minor seventh, and major seventh) (Bidelman & Krishnan, 2009, p. 13166). This distinction has received empirical support, including in recent neurophysiological research. Schön et al. (2005) investigated the experienced pleasantness and event-related brain potentials (ERPs) of consonant and dissonant intervals. They found that musicians' judgments of pleasantness were in line with the traditional music theory categorizations of intervals as perfect consonances, imperfect consonances, and dissonances. Non-musicians' pleasantness judgments did not follow this pattern, which shows that musical experience strongly influences the processing of consonance/dissonance. Furthermore, electrophysiological results revealed significant differences between the consonance categories for both musicians and non-musicians. They also found that these effects of consonance seemed to rely on the simultaneous presentation of notes (Schön et al., 2005, pp. 107, 113–116).

Johnson-Laird et al. (2012) introduced a dual-process theory of dissonance that combines "sensory dissonance" as a psychoacoustic phenomenon and "tonal dissonance," which relies on culturally learned expectations regarding tonal syntax (or "cultural familiarity"; see Cazden, 1980). Its basis is in the hypotheses of Helmholtz (1912) and Terhardt (1984). The dual-process theory of dissonance consists of four main principles: 1) tonal dissonance, which depends on scales; 2) chords with a major third are more consonant than chords with no major third; 3) chords built from thirds are more consonant than chords that are not; and 4) tonal chords sound more consonant in tonal sequence than in a random sequence (the circle of fifths is an example of a tonal sequence) (Johnson-Laird et al., 2012, pp. 24–25).

Consonance and dissonance have been examined in the traditions of both music theory and music psychology. Parncutt and Hair (2011) promote a holistic approach in which both traditions are needed. Consonance is often connected to diatonicism and centricity, while dissonance is connected to chromaticism and "acentricity," which they take as too simplifying. Around consonance/dissonance are other dichotomies to be analyzed, including diatonic/chromatic, centric/acentric, stable/unstable, tense/relaxed, similar/different, close/distant, primary/subordinate, and local/global (Parncutt & Hair, 2011, pp. 119–121).

Beats and roughness

Beats in musical tones were already known in the 19th century (see, e.g., Helmholtz, 1912, pp. 159–162). Campbell, Greated, and Myers (2004, p. 26) defined musical beats as when "the addition of the two steady notes of slightly different pitch results in a sound whose amplitude regularly rises to a maximum and dies away again. The characteristic effect resembles a series of sound pulses, and each pulse is called a beat." Hence, the frequency difference between two adjacent notes is equal to the number of beats per second. Acoustic "beats" are the result of the interference of two sound waves with slightly different frequencies (see, e.g., Garofalo, 1996). Villegas and Cohen (2010) stated, “Beats can be illustrated by the interference produced by adding two sinusoids with slightly different frequencies” (p. 76). The same authors described the concept of roughness as well: “Temporal envelope changes produced by amplitude modulation can be perceived as ‘fluctuation strength’ or ‘roughness,’ depending upon the modulation rate” (Villegas & Cohen, 2010, pp. 76–77).

Bohrer (2002) argues that the minimization of beats defines consonance (in psychoacoustic terms). This involves the presence of beats at the levels of both the fundamental and harmonics. The perception of roughness gives dissonance its character. Beat perception is connected to the arithmetic difference between the frequencies involved. In Bohrer’s terminology, dissonant intervals tuned according to the harmonic series can be called the *harmonic series principle*, which says that there is roughness but no extra beats (Bohrer, 2002, p. 53). In particular, the beats of high-frequency components help us understand musical consonance and harmony (Villegas & Cohen, 2010, p. 76).

2.1.4 Pythagorean tuning

The concepts of consonance and dissonance have been fundamental to music theory since ancient Greece. An early attempt to define consonance and dissonance is found in the number ratios of Pythagorean tuning (Duffin, 2007, p. 463; Gordon, 1983, p. 21; Jeans, 1937, pp. 166–172; Rasch, 2002; Sethares, 2005, pp. 52–56; Von Helmholtz, 1912, p. 433; Weiss & Taruskin, 2007, pp. 2–4; White, 1975; Wood, 1975, pp. 137–140). According to legend, Pythagoras noticed that consonant (pure, in tune) intervals corresponded to small-integer ratios of string lengths on a simple string instrument called a monochord (Hall, 1974, p. 545). Pythagorean tuning is based on the prime number 3-limit, which means that basic intervals used for constructing the tuning can be accounted for by numbers that are divisible by 2 and 3 but no larger numbers (i.e., 2:1, 3:2, 4:3, and 9:8).

Pythagorean tuning is arrived at by tuning a succession of 12 perfect fifths from an arbitrary reference pitch. To keep the pitches in the same octave range, some of the 3:2 ratios in the succession have to be divided by 2 (Scholtz, 1998, pp. 7–8). Thus, dividing by 2 converts fifths to fourths in the opposite registral direction. Simply put, Pythagorean tuning is merely a series of pure (3:2) fifths piled in a successive chain. Yet, if there are 12 fifths in the chain, the pitch of B# is 23.46 cents higher than the original pitch (supposing octave equivalence). The ratio is

531441:524288, and it is called the Pythagorean comma or ditonic comma. An equation that demonstrates the discrepancy called a ditonic comma (Pythagorean comma; 23.4 cents) is

$$3^{12}:2^{19} = 531442:524288 \text{ (cf. Hall, 1974, p. 544).}$$

The practical importance depends on context. String instruments are normally tuned in perfect fifths. This will result in, with violin, the E-string being "high" (408 cents) when compared to a justly intonated major third (386 cents) in the situation where C-note is the perfect fourth of the G major scale. As successive perfect fifths are compiled into the one-octave range, the result is the scale introduced in Table 1.

Table 1. Ratios and cents of the Pythagorean tuning scale.

Interval	Ratio	Cents
Unison	1:1	0
Minor 2nd	256:243	90
Major 2nd	9:8	204
Minor 3rd	32:27	294
Major 3rd	81:64	408
Perfect 4th	4:3	498
Augmented 4th	729:512	612
Perfect 5th	3:2	702
Minor 6th	128:81	792
Major 6th	27:16	906
Minor 7th	16:9	996
Major 7th	243:128	1110
Octave	2:1	1200

It is notable that the major third of the Pythagorean tuning is even wider (408 cents) than our familiar equal-tempered major third (400 cents). Wide thirds and sixths were considered dissonances in early music periods (Bohrer, 2002, pp. 26–28). Because the major third was treated as a dissonance, polyphonic compositions were composed in organum (medieval polyphonic music in the 12th–13th centuries), which meant parallel fourths, fifths, and octaves (Zweifel, t1994, pp. 89–91). It could be said that Pythagorean tuning produces ideal fifths and fourths and tensioned thirds and sixths. Duffin (2007, p. 463) argues that the imperfection of major thirds is the principal shortcoming in this tuning system. According to many commentators, Pythagorean intonation should be used in medieval repertoires (Di Veroli, 1978, p. 223; Zweifel, 1994, p. 90).

2.1.5 Just intonation and the syntonic comma

The diatonic just intonation scale can be formed by searching for the tonal functions from harmonic series. As is widely known, the tonic triad consists of the perfect fifth and major third. In the harmonic series, the perfect fifth comes from the relationship between the third and second partials, thus corresponding to the ratio of 3:2. The major third consists of the ratio 5:4, which is the relationship between the fourth and fifth partials. Assuming the fundamental tone as C, we may determine the notes E and G in this way (e.g., Ellis 1874; see also Backus, 1977; Barbour, 1951/2004; Gordon, 1983; Jeans, 1937; Partch, 1974; Pierce, 1983; Sethares, 2005; Von Helmholtz, 1912; Wood, 1975).

It is possible to adopt the dominant triad directly from the harmonic series, as well. The root of the dominant triad would thus correspond to the third partial. The fifth of the dominant triad is the ninth partial, and the third is the 15th partial. Hence, the ratios involved are 15:9:3. All three ratios are divisible by 3. 15:9:3 = 5:3:1. The latter ratio reveals that the dominant triad is formally a major triad, just like the tonic one. The tones of the subdominant triad cannot be directly found in the harmonic series. One way of generating the subdominant triad is to simply take a perfect fifth downward from the reference tone (the fundamental of the original harmonic series discussed above), thus arriving at F from C, for instance. Then a major third (5:4) must be added to the subdominant root of F. The fifth of the triad, C-tone, is already present as the original fundamental tone, C. Following this line of thought, we get three pure or "just" major triads representing three tonal functions: tonic, dominant, and subdominant. Three pure major triads constitute the basis of the just intonation scale. The scale can be illustrated as a two-dimensional lattice consisting of a "fifth dimension" and a "third dimension" (see Fig. 3), which shows the white keys of the just intonation scale, so to speak.

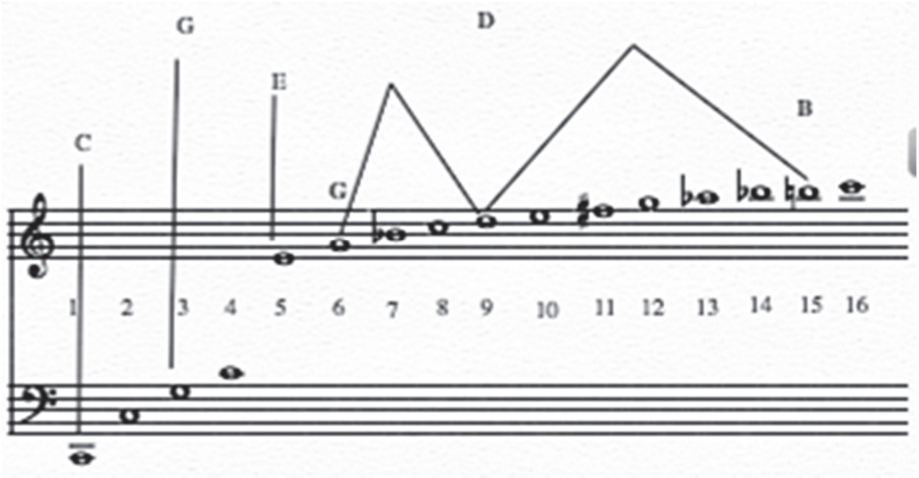

Fig. 2. The tonic triad and dominant triad, presented in a harmonic spectrum.

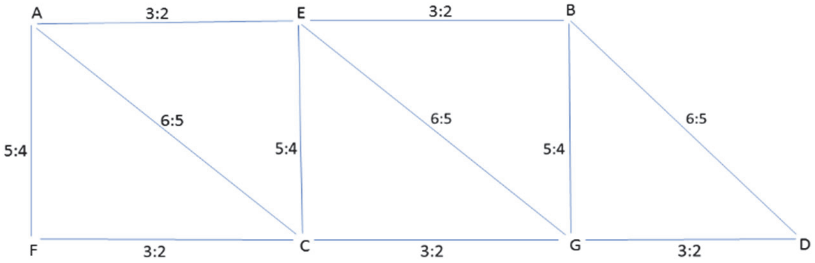

Fig. 3. Just intonation diatonic scale presented as a two-dimensional lattice.

Table 2 lists the various intervals found within the lattice of Fig. 3. The intervals are arranged as a half-matrix adopted from Polansky, Rockmore, Johnson, Repetto, and Pan (2009, p. 75). In addition to frequency ratios, I have also included interval sizes in cents. The most important details to be noted concern the intervals D–F and D–A, both of which are narrower in size than the corresponding justly tuned intervals. Technically, both of these intervals are narrow by the small amount of 21.51 cents, known as the syntonic comma. This is the difference between the just perfect fifth (3:2) and the “non-ideal” perfect fifth, “grave fifth,” or “Wolf” fifth (40/27) (see Polansky et al., 2009, p. 75). Likewise, it is the difference between the just minor third (6:5) and the Pythagorean minor third (32/27) that reappears here at D–F.

Table 2. Interval half-matrix of the just diatonic scale.

No.	C	D	E	F	G	A	B	C
C		9/8	5/4	4/3	3/2	5/3	15/8	2/1
		203.91	386.31	498.05	701.95	884.37	1088.27	1200.00
D			10/9	32/27	4/3	40/27	5/3	16/9
			182.40	294.14	498.05	680.45	884.37	996.09
E				16/15	6/5	4/3	3/2	8/5
				111.73	315.64	498.05	701.95	813.68
F					9/8	5/4	45/32	3/2
					203.91	386.31	590.22	701.95
G						10/9	5/4	4/3
						182.40	386.31	498.05
A							9/8	6/5
							203.91	315.64
B								16/15
								111.73

Syntonic comma, the conflict between the pure major third and the perfect fifth

As noted earlier, the difference between the major third counted from four ascending fifths and a major third (5:4) is called the syntonic comma (81:80) (cf. Hall, 1974, pp. 547–548). The four unavoidable tuning discrepancies, according to Zweifel (1994, pp. 92–93, 113) are the following:

1. The syntonic comma is the ratio that is achieved by the sequence of four perfect fifths (3:2). The resulting pitch has to be brought down twice to stay within the octave. The major third that is achieved is wider than the just major third. The difference between those two major thirds is the ratio of 81/80, the syntonic comma. The definition (four pure fourths—two pure octaves—major third) = 21.51 cents.
2. The ditonic comma (Pythagorean comma) is the ratio achieved with the sequence of 12 fifths (the complete circle of fifths). The final tone, B#, is sharper than C. The definition (12 perfect fifths—seven perfect octaves) = 23.5 cents, with a ratio of 531441:524288.
3. The lesser diesis is the difference between the perfect octave and three major thirds (5:4), and the octave is wider. The definition (the octave—three major thirds) = 41.1 cents, and the ratio is 128/125.

4. The greater diesis is the difference between four minor thirds (6:5) and the octave. The sequence of these four minor thirds clearly produces a wider interval than the octave. The definition (four minor thirds—the perfect octave) = 62.6 cents, with the ratio 648/625.

According to Zweifel (1994), the just scale can be expanded into the full chromatic scale by using the discrepancies and the relations. The pitch of Ab can be defined by the relationship to C (Ab-C = 5/4, M3). This can be parsed as Ab/C = 2 : 5/4 = 8/5. Notice that within an extended just intonation system (see Fig. 4), this Ab might also have to be used as a substitute for the note G#—say, as the third of an E major chord. In this context, however, the note Ab would be higher than a just G# by a *lesser diesis* (41.1 cents). This can be analyzed as G#/C = (5/4 × 5/4 = 25/16). The interval between Ab and Gb is a minor whole tone (10/9 = 182 cents). However, the interval between G# and F# is a major whole tone (9/8 = 204 cents). Because of the difference between the minor whole tone and major whole tone (the syntonic comma = 21.506 cents), the interval Gb/F# expands by a syntonic comma. The syntonic comma added to the lesser diesis (41.1 cents) gives the greater diesis (62.6 cents). This can be analyzed as Gb/F# = G#/F# × Ab/G# : Ab/Gb. This can be expressed algebraically as the major whole tone + the lesser diesis − the minor whole tone = the lesser diesis + the syntonic comma = the greater diesis (Zweifel, 1994, pp. 96–98).

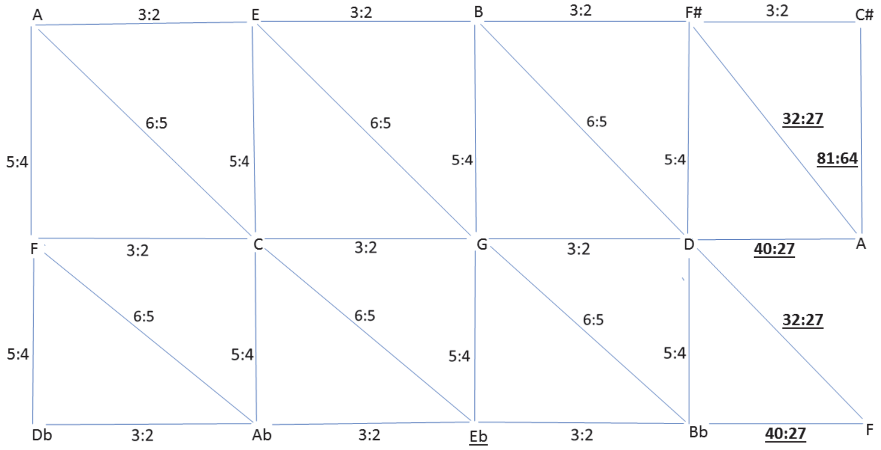

Fig. 4. Just intonation chromatic scale presented as a two-dimensional lattice.

Complementing the just scale, Zweifel (1994) introduced an axiom of chromatic invariance stating that the interval between any pair of notes is not affected by chromatic alteration. This leads to the theorem that all augmented unisons in total are 71 cents. For example, the difference between B and B# can be calculated. B has a ratio of 15/8 = 1088 cents. B# is the result of three major thirds (5/4), which gives the value of 1159 cents. This is the perfect octave (1200 cents) and the lesser diesis (41.1 cents). The difference between B and B# is 71 cents (1159 − 1088). It can be expressed as | X − X# | = 71 cents, and similarly true is X# − X## | = 71 cents. Correspondingly, | Xb − X | = 71 cents, and | Xbb − Xb | = 71 cents. One can test this theorem by calculating Ab–G#. If Ab − A is 71 cents, G − A is 182 cents, and, finally, G# − G is 71 cents and can be parsed as −71 cents + 182 cents – 71 cents. This gives 40 cents, which is an approximation of the lesser diesis, which is in fact the classic example (Zweifel, 1994, pp. 99–101).

The chromatically extended just intonation scale differs essentially from the Pythagorean tuning scale in the sizes of thirds and sixths and semitones and major seventh. Fifths, fourths, octaves, and the major whole tones are the same because they are derived from simple integer ratios of 2 and 3. Zweifel (1994, pp. 94–97) shows the relationships of these four discrepancies:

the syntonic comma = the greater diesis − the lesser diesis
81/80 = (648/625) : (128/125).

the lesser diesis + the ditonic comma = three syntonic commas
(128/125) × (312/219) = (81/80)3.

The difference between the whole tones (9:8) and (10:9) is also a syntonic comma, 9/8 : 10/9 = 81/80. Similarly, the interval that consists of the cycle of three perfect fifths is higher than the major sixth (5:3) by a syntonic comma (Zweifel, 1994, pp. 94–97).

The utility of just intonation

Blackwood (1985) has listed several principles describing just tuning, including that octaves, perfect fifths, perfect fourths, and major and minor triads have to be pure. This means that Pythagorean thirds and sixths have to be avoided, if possible, which in turn means avoiding high leading tones. Blackwood notes that this is possible if the third of a major triad is lowered by a syntonic comma (compared to Pythagorean intonation). Respectively, the third of a minor triad must be raised by a syntonic comma (compared to Pythagorean intonation). Another way to make this minor triad pure is to lower the root and the fifth by a syntonic comma, which minimizes the risk of occurrence of the syntonic comma in melodic lines. In the case of minor keys in just tuning, the aim should be to maximize the number of tones from the relative major scale using the syntonic comma (Blackwood, 1985, pp. 129–130). The fourth degree in the minor scale and the second degree in the major scale give the possibility of adjusting pitches by a syntonic comma.

Cuffman (2016) presented an introduction to just intonation through string quartet playing. The players in a string quartet usually make intonation adjustments based on the melodic line of their part. Music students may be unaware of the differences between melodic and harmonic intonation. Cuffman argues that melodic intonation is often determined by Pythagorean intonation, whereas harmonic intonation is based on just intonation. A horizontal approach to intonation is present through education, where learning harmony belongs to chamber music playing. The study by Cuffman presents 34 examples for improvement of intonation concerning intervals, chords, and harmonic progression from the standpoint of a string quartet. Cuffman (2016) points out quite ordinary successions of double stops where the player needs to adjust common notes by a syntonic comma in order for the successive harmonic intervals to be purely tuned (pp. 26–29, 32).

Bohrer (2002) wrote that the implementation of pure intonation gives the natural basis of extended, flexible intonation. It includes the idea of mutable notes, which are natural events in enharmonic passages. The harmonic complexity of musical passages determines how many notes have to be mutable. In simple passages, the second degree of the major key and the second and seventh degrees of the minor key would necessarily involve mutable notes (Bohrer, 2002, pp. 54–55).

Pure intonation demands an increase in the number of pitches per octave. Some investigators added extra keys for keyboard instruments. Examples include Ellis's Duodenarium, Colin Brown's voice harmonium, General Perronet Thompson's enharmonic organ, Henry Ward's Poole's organ, and Bosanquet's generalized keyboard implements, the 53-tone equal temperament (Bohrer, 2002, p. 31).

Werntz (2001) claims that just intonation theory has fundamental weaknesses with theoretical premises, and there are also fundamental practical limitations when applying just intonation principles. Just intonation is a one-dimensional musical conception, specifically, a vertical view of music. Werntz claims that it includes a belief according to which music is generated by harmony (Werntz, 2001, pp. 163–165). Ternström and Karna (2011) argue, "There is no inherent advantage of using just intonation in choir music” (p. 280). Blackwood (1985) analyzed an extract from César Franck’s Symphony in D minor and concluded that just tuning was inappropriate for that piece of music. In general, Blackwood was not able to find any professional composer whose style could be adapted to the limitations of just tuning. He claimed that just tuning is of no practical use among the Western repertoire (Blackwood, 1985, pp. 150, 153). In a rather complex tonal music repertoire, the necessity of temper thirds or fifths is so complex that Blackwood’s comment is understandable.

In a performance context, differences within 1 or 2 cents would have little practical consequence for musicians (Spiegel & Watson, 1984, p. 1694). The difference between the perfect fifth (3:2 = 702 cents) in just intonation and equal temperament (700 cents) is an illustrative example of this. Hall (1974) says that “there does not exist any arrangement which constitutes a ‘tuning’ for both fifths and thirds” (p. 547). Hall denotes the musical scale of 12 notes/octave.

Barbour (1951/2004) argued that performers’ intonations include errors most of the time. These errors are the deviations from equal temperament that Barbour considered to be the standard of intonation. Music with a lot of chromaticism makes professional singers flounder in intonation and makes just intonation singing impossible (Barbour, 1951/2004, pp. 196–198). He was remarkably strict in relation to just intonation, saying, “Just intonation is [a] very limited, cumbersome and unsatisfactory tuning system” (Barbour, 1938, p. 48).

It is obvious that an analytical approach to most simple harmony gives evidence of how far just intonation can reach. In this study, beat-free triadic chord progressions are charted in Experiment 1 (see Chapter 3) and Experiment 2 (see Chapter 4).

2.1.6 Keyboard temperaments

Temperaments for keyboards are concrete implications of tempering intervals. Simplifying the issue, this means that the pure intervals derived from a harmonic series are slightly altered in keyboard temperaments—that is, made impure—such that it renders the temperament usable in more than one key. This alteration happens by distributing the syntonic comma around the scale being used. The history of Western music recognizes a vast number of keyboard temperaments that have been employed during various style periods.

Meantone tuning

The aforementioned Pythagorean tuning leaves perfect fifths pure but produces wide major thirds and narrow minor thirds, as noted in the previous sub-chapter. Meantone tuning leaves thirds pure but tempers fifths (see, e.g., Backus, 1977; Barbour, 1951/2004; Chuckrow, 2006; Jeans, 1937; Kassel & Bush, 2006; Lindley, 1990; Neuwirth, 2012; Rasch, 2002; Sethares, 2005; Von Helmholtz, 1912; Wood, 1975). Within these two extremes, there is a large number of compromise tunings, which lets all intervals be tempered (Hall, 1974, p. 546). Hall argued that meantone tuning replaced Pythagorean tuning because the syntonic comma error is split equally among four fifths. At the same time, the related third is just. According to Hall, it is easier for the human ear to detect mistuning in a fifth than in a third (Hall, 1974, p. 550).

Meantone tuning could be used practically in one key at a time, depending on composition, and it was usual for meantone tuning to be tuned separately for various keys. Therefore, music could not modulate in the way that is common today. Di Veroli (1978) argues that the standard meantone temperament should be used in Renaissance and baroque repertoires. In addition, singers should be preceded by sharp/flat alternatives (Di Veroli, 1978, p. 223 a-b).

The 1/4 comma meantone tuning enables pure thirds (386 cents) for C–E, D–F#, Eb–G, E–G#, F–A, G–B, A–C#, and A#–D. The last interval is, of course, a diminished fourth, but in a fixed temperament, it is also used as the major third. Conversely, the perfect fifths have been narrowed by 5.43 cents, which is 1/4 of a syntonic comma (21.51 cents). The syntonic comma here is the difference between the major whole tone (9:8 = 204 cents) and minor whole tone (10:9 = 182 cents). These intervals form a pure major third (5:4 = 386 cents). In this tuning, the major third is split into two equal intervals, which gives 193 cents, and this procedure was translated to the name “meantone.” The 1/4 comma meantone tuning will be used in Experiment 2; it is presented in Table 3.

Table 3. The 1/4 comma meantone tuning scale from Pietro Aaron (1523) compared to the 5-limit just intonation scale and Pythagorean tuning scale, in cents.

Pitch	Pythagorean tuning scale in cents	5-limit just intonation	Meantone tuning scale in cents
C	0	0	0
C#	90	112	76
D	204	204	193
Eb	294	316	310
E	408	386	386
F	498	498	503
F#	612	590	580
G	702	702	697
G#	792	814	773
A	906	884	890
A#	996	1018	1007
B	1110	1088	1083
C	1200	1200	1200

Well temperaments

The terms *well temperaments*, *circulating temperaments*, and *irregular temperaments* all refer to 12-tone scales in which the wolf fifth is distributed to several fifths. This enables 12 possible key signatures, including fifths that are more or less tolerable. Irregular temperaments lived side by side with meantone tuning during the 17th century and were used for two centuries (Benson, 2006, p. 181). Sponsler (2011, pp. 8–9) emphasizes that well temperaments distributed the comma in various ways that led to a particular sense of character in different keys. This was known among composers. Well temperaments also tempered major thirds, not just perfect fifths. Benson (2006, p. 183) refers to the key characteristics originally published by Christian Schubart in his book *Ideen zu ainer Aesthetik der Tonkunst* (1806). Different key signatures have their own character among irregular temperaments (see e.g., Barbour, 1951/2004; Benade, 1990; Chuckrow, 2006; Cyr, 2017; Rowland, 2001; Sethares, 2005).

The term “well tempered” comes from Johann Sebastian Bach’s (1685–1750) *Das Wohltemperierte Clavier*. During his time, Andreas Werckmeister (1645–1706) used this term as the title of his first published book, *Erweiterte und Verbesserte Orgel-Probe* (1681/1976). Werckmeister developed six temperaments named according to him. Werckmeister I tuning (in the following table) was picked up from his 1691 book, *Musikalische Temperatur* (2nd ed.), which came with a copperplated monochord that he gravely referred his readers to for further tuning information (Reinhard, 2016, p. 37).

In his first two temperaments, Werckmeister experienced the need for more than 12 notes per octave (Reinhard 2009, p. 53). Hence, Werckmeister I tuning included as many pure triads as possible, which can be seen in Table 4.

Table 4. Werckmeister I tuning with just intonation to 20 pitches/octave (adapted from Reinhard, 2009, p. 51).

C	C#	Db	Ds	D1	D#	Eb	E	F	F#	Gb	G	G#	Ab	As	A1	Bb	A#	Bb	B
										No					No	No			
										3:2					3:2	3:2			
0	71	112	182	204	275	316	386	498	569	590	702	773	814	884	906	977	996	1018	1088
	No				No				No			No			No				
	5:4				5:4				5:4			5:4			5:4				

Werckmeister I gives 17 justly tuned perfect fifths. Conversely, Gb-Db is 722 cents, A1-E is 680 cents, and Bb-F is also 680 cents. In addition, there are 15 justly tuned major thirds. However, the major thirds to C#, D#, F#, G#, and A1 are not pure, so there are 13 justly tuned major triads left.

Werckmeister II Tuning is called *quarter-comma meantone* tuning although it is chromatically extended to allow more than 12 pitches per octave to be played with a split-key keyboard (Reinhard 2009, p. 53). In addition, Werckmeister III, IV, V, and VI and Werckmeister 1698 are counted as “well temperaments” (wohl-temperiert). Werckmeister developed these as alternatives to an imperfect meantone tuning that, as already mentioned, had limitations and wolf intervals (Reinhard, 2016, pp. 32–39). The differences between meantone and Werckmeister III were quite minimal, as Table 5 shows. However, the latter was the first “circular” well temperament, which means that the modulation of keys is possible. Werckmeister V is rather close to equal temperament, which is introduced in the next sub-chapter.

Table 5. The 1/4 comma meantone scale compared with the Werckmeister III and Werckmeister V scales.

Note	1/4 Comma meantone tuning	Werckmeister III well temperament	Werckmeister V
C	0	0	0
C# and Db	76	90	96
D	193	192	204
D# and Eb	310	294	300
E	386	390	396
F	503	498	504
F# and Gb	580	588	600
G	697	696	702
G# and Ab	773	792	792
A	890	888	900
A# and Bb	1007	996	1002
B	1083	1092	1098
C	1200	1200	1200

The aforementioned temperaments are only a thin sample of irregular temperaments in Western music, but they give some perspective on the abundance of tuning systems and temperaments used. According to Benson (2006, pp. 184–186), in addition to Werckmeister, irregular temperaments were developed by at least Mersenne (1644), Bendeler (1690/1739), Neidhardt (1724), Kirnberger (1764, 1779), Lambert (1774), Marpurg (1776), Barca (1786), Vallotti (1780), and Young (1800).

Equal temperament

Described as the simpliest, the equal temperament scale is divided into 12 pitches with equal distance. The semitones of equal temperament originate from the frequency ratio 1:1.05946 invented by French mathematician Mercenne in the book *Harmonie Universelle* (1636) (Jeans 1987, p. 174). The formula is (White, 1975, p. 398):

$$n\ 12 = 2$$
$$n = (2)^{1/12} = 1.05946.$$

In fact, the pitches of the equal temperament scale are closer to Pythagorean tuning than just intonation. The equal temperament scale is widely discussed in the literature (see, e.g., Backus, 1977; Benade, 1990; Gordon, 1983; Jeans, 1937;

Sethares, 2005; Von Helmholtz, 1912; Wood, 1975). Table 6 introduces the frequency ratios, frequencies (Hz), and cents of equal temperament and compares them to the cent values of Pythagorean tuning.

Table 6. Frequency ratios, frequencies (Hz), and cents of equal temperament compared to Pythagorean tuning.

Note	ET[1] frequency ratio	ET frequency in hertz (Hz) (A4 = 440 Hz)	ET in cents	Pythagorean tuning in cents
C	1.000	262	0	0
C# and Db	1.059	277	100	90
D	1.122	294	200	204
D# and Eb	1.189	311	300	294
E	1.260	330	400	408
F	1.335	349	500	498
F# and Gb	1.414	370	600	612
G	1.498	392	700	702
G# and Ab	1.587	415	800	792
A	1.682	440	900	906
A# and Bb	1.782	466	1000	996
B	1.888	494	1100	1110
C	2.000	523	1200	1200

[1] ET = equal temperament

Concerning enharmonic pairs of equal temperament, 12 perfect fifths give from Eb the pitch for D#, which is higher than Eb (from the chain of seven perfect octaves) by a Pythagorean comma. To get D# and Eb to the same pitch, the fifths have to be tempered by a 1/12 Pythagorean comma. The perfect fifth is 702 in cents. The fifth in the equal temperament is 700 cents. This leads to enharmonic pairs of the equal temperament (Scholtz, 1998, pp. 5–6).

Bohrer (2002) says that the effort to minimize impurities is an essential feature of temperaments as they attempt to close the octave range within a fixed number of pitches. This led to an endless number of temperaments, and the final destination was equal temperament. It was the extreme compromise between consonance and the number of fixed keys per octave—transpositions were to sound homogenized (Bohrer, 2002, p. 43). Jorgensen (1991) described the situation before 1917, when tempering intervals of keyboard instruments was an art based on an enthusiastic sense of key colors for each individual interval or chord. But with equal temperament, this sense of color has disappeared (Jorgensen, 1991, p. 3). Blackwood (1985) says, “The equal tuning theorem states that if all the pitches forming any closed circle of intervals are reproduced in all registers by octave transpositions, the result is an equal tuning" (p. 226). The temperaments other than 12-tone equal temperament are limited to certain historical periods. According to Blackwood (1985), equal temperament is the most appropriate temperament for all polyphonic music, despite it being imperfect (Blackwood, 1985, p. 244). Violinist and professor of music performance Mieko Kanno (2003) considered the generalization of equal temperament and its effects on violin playing and intonation strategies, saying, "The vital link between composition and performance was broken. Intonation became an issue of performance practice alone" (p. 36).

The equal temperament was used from the middle of the 19th century with pianos and organs, and it was used in fretted guitars and lutes even before that (Scholtz, 1998, pp. 4–5). Sethares (1994) says: "Just intonations (and the related scales) sacrifice the ability to modulate music through multiple keys, while 12-tone equal temperament sacrifices the consonance of intervals" (p. 17). The above brief presentation of central tuning systems in Western music can be summarized in the comparison given in Table 7.

Table 7. Pythagorean tuning, 5-limit just intonation, 1/4 comma meantone tuning, Werckmeister III, Werckmeister V, and equal temperament scales in cents.

Note	PT[1]	5-limit JI[2]	1/4 comma MT[3]	Werckmeister III well temperament	Werckmeister V	Equal temperament
C	0	0	0	0	0	0
C# and Db	90	112	76	90	96	100
D	204	204	193	192	204	200
D# and Eb	294	316	310	294	300	300
E	408	386	386	390	396	400
F	498	498	503	498	504	500
F# and Gb	612	590	580	588	600	600
G	702	702	697	696	702	700
G# and Ab	792	814	773	792	792	800
A	906	884	890	888	900	900
A# and Bb	996	1018	1007	996	1002	1000
B	1110	1088	1083	1092	1098	1100
C	1200	1200	1200	1200	1200	1200

[1] PT = Pythagorean tuning, [2] JI = just intonation [3] MT = meantone tuning

Bohrer (2002) argues that equal temperament sets requirements that are difficult to satisfy in a cappella singing; singers can hardly replicate a tuning built on fixed-layout instruments. However, counting beats is not feasible in a performance situation. Performers often ignore the deviations from the various tuning systems, and the fixed layout of the keyboard strongly influences intonational strategies. There are hundreds of temperaments, all of them imperfect. At the same time, there has been no attempt to provide for a flexible procedure toward intonation (Bohrer, 2002, p. 51).

2.1.7 Pitch drift

Pitch drift was already known in the 16th century. The example in Fig. 5 illustrates the phenomenon of pitch drift that takes place while keeping the note A of the soprano voice stationary in the first two bars.

Between the two upper voices, the first two bars of the example would urge us to first tune a pure fifth between D and A, and then, keeping the latter note in place, a pure fourth between E and A. Considering the example with the just intonation lattice in Fig. 3 in mind, we would start from the D at the far right of the lattice, reaching out from the lattice by two new horizontal steps to the right: D–A–E. Thus, we would have arrived at a new E that is no longer the one seen in the original lattice. More technically speaking, the notes E and C in the second bar would have to be raised by a syntonic comma to make the intervals E–A (4:3) and C–A (5:3) pure. This happens four times in the example. Here, maximizing the purity in vertical intervals gradually leads to a pitch drift by four syntonic commas, amounting to a shift of fundamental frequency by 86 cents, or almost a semitone.

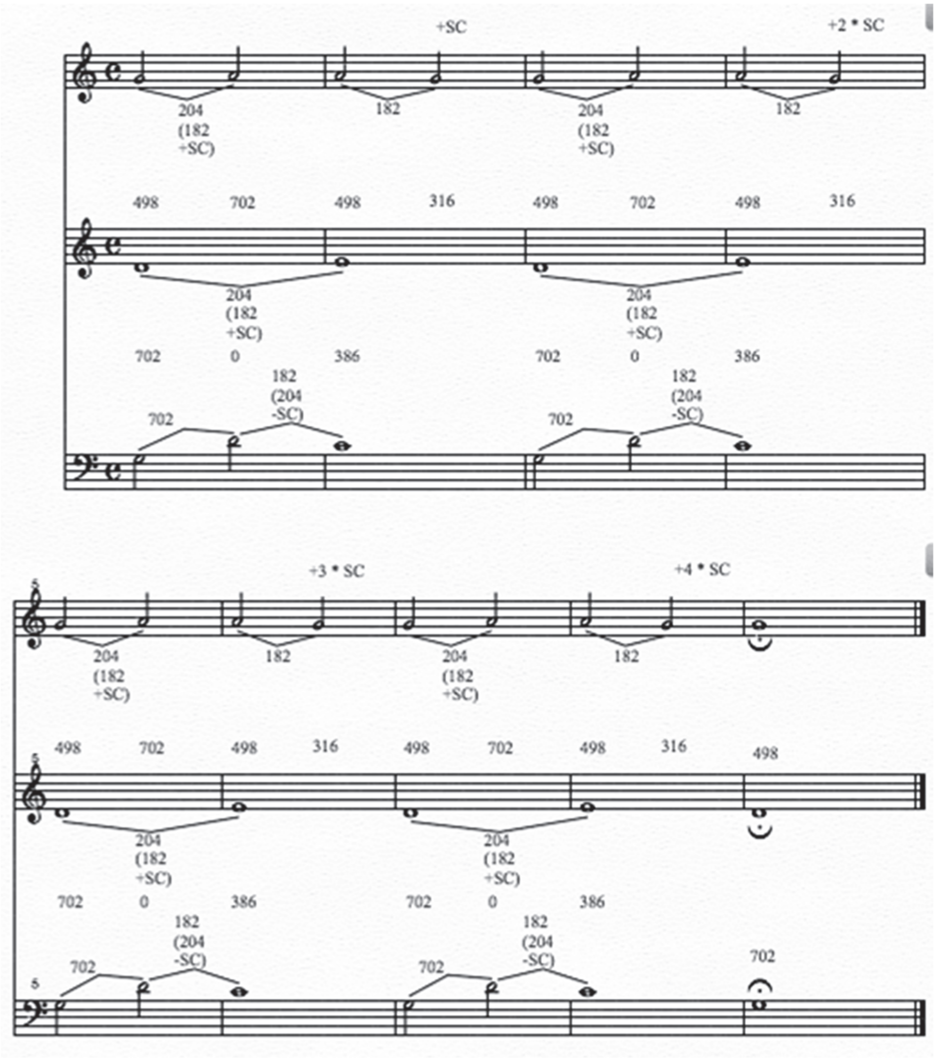

Fig. 5. Giovanni Benedetti 1563: Drift by a comma during a progression, with intonation analysis of the author.

Pitch drift may also take place in quite ordinary harmonic progressions (Hall, 1974, p. 549). He illustrates pitch drift with the typical tonal cadence I – vi – ii^{6} – V – I. In Fig. 6, I have added an intonation analysis to Hall's example of pitch drift. Let us first consider what would happen if the example were performed in just intonation, without pitch drift. In just intonation, all vertical triads in the example could be tuned according to small-integer ratios, except the ii^6 triad on the third beat of the first bar. Holding on to the fixed pitches of the just intonation scale, the ii^6 triad would be mistuned by a syntonic comma (21.51 cents; see Table 2).

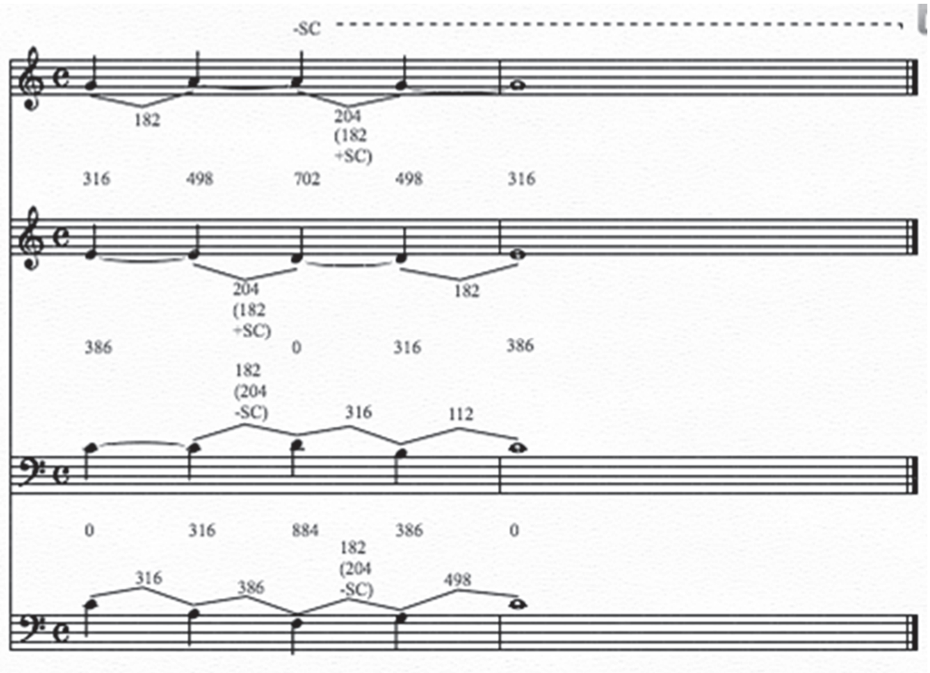

Fig. 6. Intonation analysis of the cadence I – vi – ii6 – V – I by the author.

To avoid the mistuned ii^6 triad, there is not much to do. Theoretically, we could raise the A in soprano (third beat of the bar) to form a pure fifth (702 cents) with D. However, this note is tied to the second beat of the bar. It might not seem appropriate to raise the tied A by a syntonic comma because of voice leading and tradition. So, it is better to keep the A stable. But then we are forced to lower the D of the ii^6 triad to make that triad pure. Then, to make the next V triad pure, we must remember that the fifth of the dominant triad was lowered by a syntonic comma (to make the ii^6 triad pure). Now D of this ii^6 triad is tied to the next bar, so the root and the third of the V triad have to be lowered by a syntonic comma. The consequence is, of course, that the melodic movements to the root of the V triad have to be altered by syntonic comma (expand downward, reduce upward). The melodic movement in tenor voice from D to B is 6:5 (316 in just intonation), but the third of the dominant triad is a syntonic comma lower than in the original pitch because the previous D was lowered. Now pitch drift has happened. The next triad will inevitably be flattened by a syntonic comma. As Hall (1974) writes, “If sung in just intonation, with each tied note being held at constant pitch, it will leave the chord 21.5 cents lower at the end than at the beginning” (p. 549). In other words, in a major key context, pitch drift is the consequence of the combination of making the ii triad pure and tying it by common notes to other chords around it. After this examination, it is much easier to understand the following remark from Hall (1974): “Anyone who thinks ‘going flat’ is evidence for lack of skill in a choir should work out the arithmetic of this example for himself” (p. 548). Barbour managed to define pitch drift, although he spoke about fluctuating:

> On the assumption that the pitch of a repeated note remains constant in successive chords, the pitch of the key will not vary so long as the roots of chords move by fourth or by fifths; but if a root falls a minor third or rises a major third, the pitch is lowered by a comma; in the reverse progressions (root falling a major third or rising a minor third) the pitch is raised by a comma. (1938, p. 50)

Barbour (1938) uses the first phrase of *God Save the King* as an example. He seems to have thought that the origin of pitch drift lies in certain root progressions, but as a matter of fact, his generalization is not completely correct. For example, a I–iii movement in a major key would not lead to pitch drift, although chord roots are related by a major third. As the following intonation analysis of Barbour’s sample shows, the reason for pitch drift is, again, in achieving a vertically pure ii triad in a context where it shares some pitches with the surrounding chords. One of the root progressions that Barbour points out—a falling minor third—indeed takes place between the two first chords (I–vi), but what is important in this is the resulting note E in the alto voice, representing the sixth degree of the G major scale. As this note is repeated in the following ii^6 triad, it forces the root in the soprano voice to be lowered by a syntonic comma in order to create a vertically pure ii^6 triad. The lowered ii^6 root will draw the rest of the voices downward in the subsequent melodic movements leading to the next chord. Hence, the melodic movements from the third and fifth ii^6 triads (across the first barline in Fig. 7) are all altered by a syntonic comma.

Fig. 7. The author's intonation analysis of *God Save the King*.

In Fig. 8, I took the passage from Howard's (2007b) study, where it is used to illustrate pitch drift, and made an analysis of it. The analysis shows that the fundamental frequency falls no less than 129 cents if vertical triads stay in just intonation.

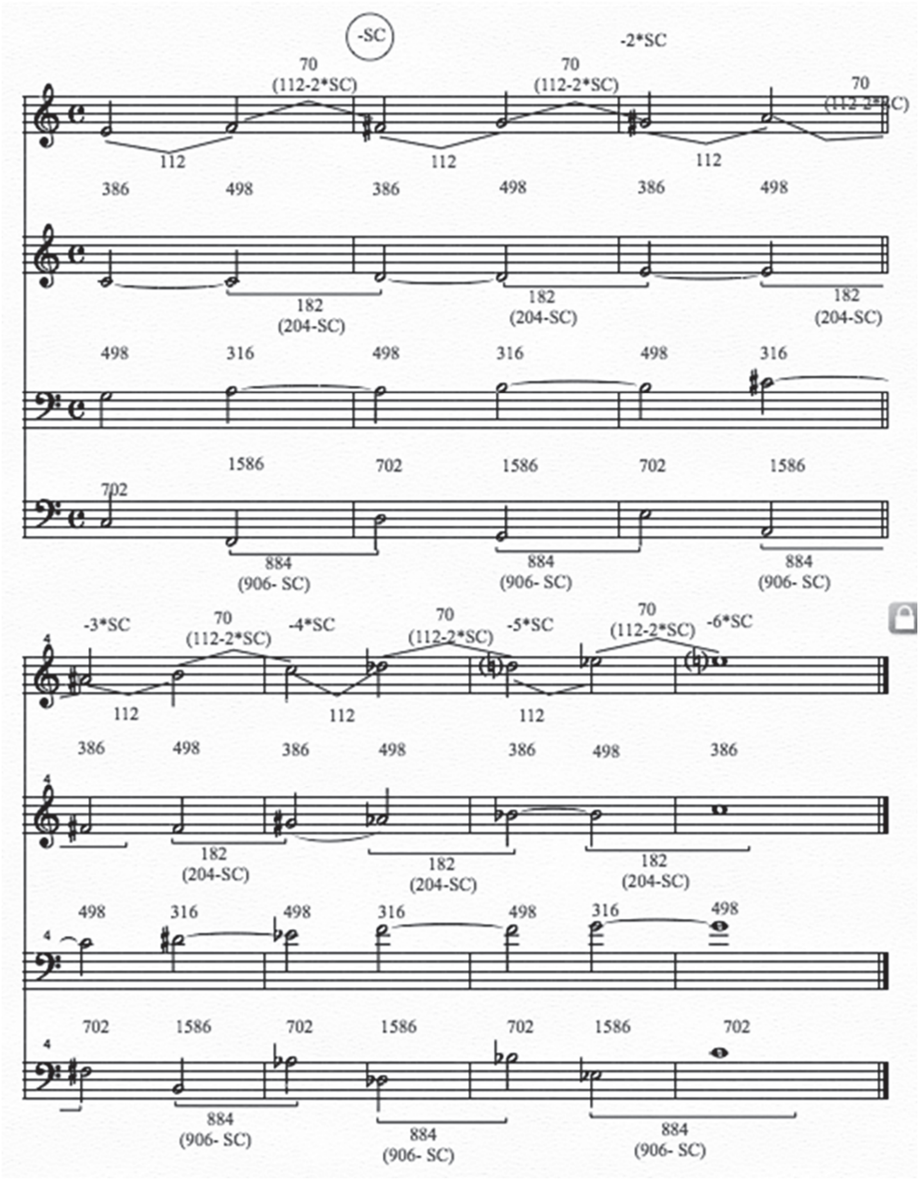

Fig. 8. The author’s intonation analysis of the exercise from Howard (2007b, p. 88).

The previous examples of pitch drift demonstrated the phenomenon by means of examples from the research literature. In typical tonal harmonic contexts, pitch drift occurs around the ii triad. In order to achieve pure intonation of this triad, either its root is lowered by a syntonic comma (pitch drift down), or its third and fifth are raised by a syntonic comma (pitch drift up). The mistuning of the ii triad is thus transferred to the melodic movements around it. To sum up, there are two possibilities for pitch drift (in a major key context):

- Pitch drift up: The third and the fifth of the ii triad are raised by a syntonic comma:
    - If the root of the ii triad is kept stable at 204 cents from the tonic note (according to just intonation), the melodic movements to the third and fifth of this triad have to be raised by a syntonic comma compared with melodic movements of original pitch in just intonation.
    - Thereafter, the melodic movement from the root of the ii triad has to be raised by a syntonic comma, completing the upward pitch drift (compared with melodic movements of the original pitch in just intonation).
    - The common tied notes are kept stationary, and the tuning of the following chord is defined by it.
- Pitch drift down: The root of the ii triad is lowered by a syntonic comma:
    - If the third and fifth of the ii triad are kept stable at 498 and 884 cents, respectively, from the tonic note (according to just intonation), the melodic movement to the root of this triad has to be lowered by a syntonic comma (compared with melodic movements of original pitch in just intonation).
    - Thereafter, the melodic movements from the third and fifth of the ii triad have to be lowered by a syntonic comma, completing the downward pitch drift (compared with melodic movements of the original pitch in just intonation).
    - The common tied notes are kept stationary, and the tuning of the following chord is defined by it.

In a major key just intonation context, pitch drift can thus be defined as a change of fundamental frequency as a result of a phenomenon where the second degree syntonic comma is allocated to melodic movements surrounding this triad due to keeping common notes between successive chords stationary. In fact, this demand for stationary notes explains the phenomenon where a syntonic comma transfers into melodic movements. Hence, pitch drift can also be defined as a change of fundamental frequency due to successively drifting away from the original just intonation lattice via domino-like chord changes where successive chords share common notes and where new notes are tuned as pure intervals in relation to them.

The aforementioned examples show theoretically potential situations where a syntonic comma can be transferred to melodic movements and pitch drift can happen “in the wholeness”. Of course, all these phenomena can occur imperfectly. The ii triad can stay mistuned less than 21.51 cents, and hence only a part of a syntonic comma can be allocated to melodic movements. Pitch drift may be only, say, 5–10 cents, which might be more probable than a complete pitch drift. As discussed in Sub-chapter 2.3.3, Howard (2007b) has investigated this and showed that the ditonic comma (23.5 cents), the lesser diesis (41.1 cents), and the greater diesis (62.6 cents) can be involved in pitch drift phenomena.

There have been some interesting examinations of pitch drift in recent research, and they are presented in Sub-chapter 2.4.3. Villegas and Cohen (2010) mentioned the concept of pitch drift, referring to the tendency where the actual pitches are different from those nominally determined by a certain tuning system. This necessitates the absence of fixed-pitch instruments, like keyboards. Musicians adjust intervals to a maximum consonance in consonant chords. In practice, however, musicians often try to prevent excessive pitch drift in performance (Villegas & Cohen, 2010, p. 79). This means distributing the syntonic comma over the adjusted intonation both horizontally and vertically. In temperaments, this is done by tempering, as will be remembered from Sub-chapter 2.1.6.

Stange et al. (2018) presented another example of pitch drift: playing a full chromatic scale with semitones of 16:15 (111.73 cents) will end up in an octave of 1340 cents instead of 1200 cents. Another way would be alternating sizes of 111.73 cents and 92.18 cents, which ends up at 1223.46 cents. Therefore, the authors present an equation to implement an additional pitch drift compensating mechanism (Stange et al., 2018, p. 56). This kind of perspective of pitch drift differs from the one used in this research but broadens the concept. Pitch drift phenomena that are based on chains of melodic intervals are perhaps not so probable in singing, not to mention in acoustic instrumental music. In this study, pitch drift is conceived of as a discrepancy of just intonation that is realized in tonal chord movements.

2.1.8 Harmonic and melodic intonation

The question of melodic and harmonic intonation in tonal music relates firmly to the problem of the syntonic comma previously presented in Sub-chapter 2.1.5. The understanding of pitch drift also makes the distinction of harmonic and melodic intonation more understandable. Even in very simple harmonic changes, the syntonic comma makes tangible the conflict of pure major thirds and perfect fifths.

Fyk (1995, pp. 215–219) divided intonation into the following types: melodic, harmonic, corrective, and colored intonation. Duffin (2007) discusses the phenomenon called "expressive intonation" and its relation to harmonic intonation. According to an expressive, or melodic, approach, the thirds of dominant chords should be intonated sharp and the descending leading tone, for example, Db to C, should be intonated flat, both as compared with equal temperament. By contrast, according to a harmonic point of view, the same notes would be tuned in just harmonic relations, and thus they would depart from the equal temperament in the opposite direction. The ascending leading tone should be slightly lowered and the descending leading tone slightly raised. If a musician only focuses on melodic lines, it creates a conflict with harmonic material. According to Duffin (2008), expressive intonation is a variant of equal temperament, and it works only for soloistic situations. Nowadays, many musicians use it when playing in ensembles and orchestras. The harmonic approach and vertical quality of intonation should be explored in any music that includes tonal harmony. This does not mean the abandonment of equal temperament. Musicians should be aware of non-equal temperaments as well (Duffin, 2008, pp. 19–22, 154–159).

According to Kanno (2003), aspects of intonation began to be considered outdated in the mid-twentieth century. New music rendered musical intonation less relevant for performance. In these circumstances, intonation became a topic only when some composers began to use microtones in their works, widening their pitch vocabulary. From the performer's point of view, microtonality is an empirical reflection of the relationship between what is written and what a performer can create with it (Kanno, 2003, pp. 49–52).

Devaney and Ellis (2008) refer to Backus (1969) and Barbour (1953) in noting that vocal intonation is a combination of horizontal and vertical intonation and that the weightings of these factors differ depending on musical contexts. The vertical intonation is based on the area of sensory consonance. Horizontal intonation practices in performance can be related to musical expectations, musical meaning, and emotion (Devaney & Ellis, 2008, pp. 142–147).

The following example sheds light on the dichotomy of melodic and harmonic intonation. This is the same excerpt of *God Save the King* as in Sub-chapter 2.1.7. Imagining that there was a classical singer singing the melody (top voice) and a singing ensemble singing the other voices, it is possible to end up in a confusing situation. Assuming that the top voice singer intonates the melody to the

Pythagorean direction (high major thirds and leading tones, narrow semitones, whole tones as 204 cents, which is common in melody lines), the top voice can drift to the sharp direction momentarily even two syntonic commas, which means 43 cents. Yet assuming that other voices, following just intonation, intonate vertically pure intervals with respect to one another, without being affected by the top voice, then the distance between the top voice and second voice produces unpleasant intervals (520 cents, 429 cents, 337 cents). This extremely simple example shows that practical intonation in non-fixed intonation is a continuous process.
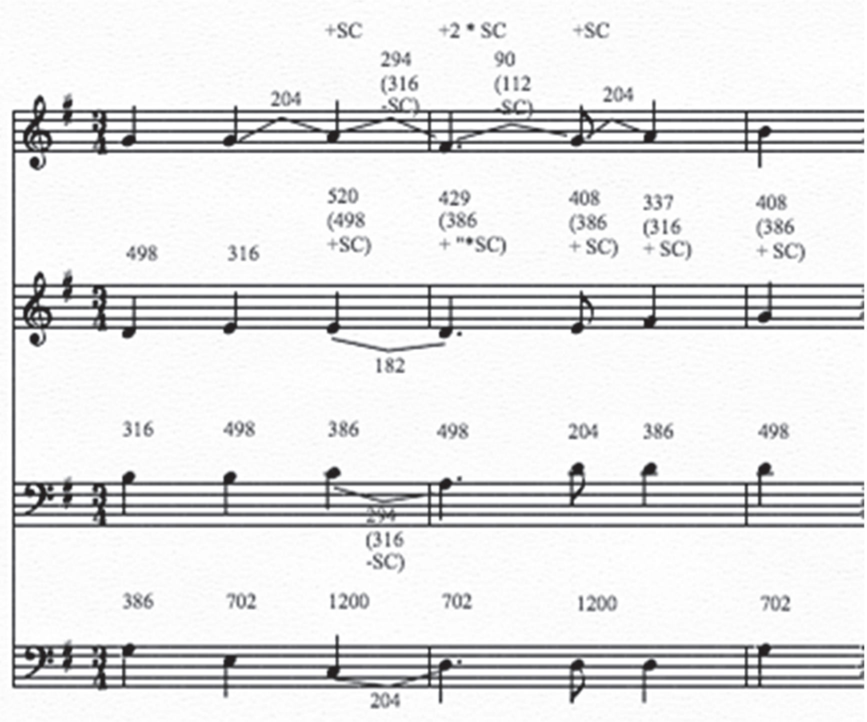
Fig. 9. An example of dichotomy of harmonic and melodic intonation.

2.2 Recognition of mistuning: Previous research

The first experiment of the present research explores the recognition of mistuned triads by a syntonic comma. In this sub-chapter, I will introduce the reader to the central previous research undertaken in this field. These studies are focused on perception and discrimination of intervals, perception of mistuning, perceived pitch of vibrato, and perception related to intonation in performance.

2.2.1 Musical interval perception

The performance and perception of intonation have been the research topic in numerous studies. I will introduce general principles of perception of musical elements, method of adjustment, identification on intervals, and categorical perception.

Pitch

Pitch is “the perceptual correlate of fundamental frequency (F0), that is, the rate at which a periodic waveform repeats itself” (de Cheveigné, 2010, p. 71). This definition is for the psychoacoustician. Pitch is the stuff of which melody, harmony, and tonality are made. Pitch (physically “periodicity”) is essential for segregating rival sound sources in perception. In spite of different amplitudes, durations, spatial positions, and spectral contents, the sound stimuli can invoke the same pitch. An accurate pitch perception can mean a superlative sensitivity to tiny changes of fundamental frequency but also a skill in ignoring huge differences in other dimensions of pitch (de Cheveigné, 2010, p. 71). Micheyl et al. (2006) wrote, “Pitch is a fundamental dimension of auditory perception, which plays an essential role in most forms of music” (p. 36). Oxenham (2013) added, “Pitch is arguably the most important dimension for conveying music” (p. 9).

General principles

Before I present an overview of prior research concerning the human ability to perceive pitch, musical intervals, and slight differences and mistunings between musical tones, it is important to realize that previous investigations of pitch perception are, on the whole, ultimately based on the pitch of pure tones or the pitch of complex tones. As Oxenham (2013) put it, “Pure tones produce a clear, unambiguous pitch, and we are very sensitive to changes in their frequency” (p. 9). Musical sounds are mostly complex tones, and most have a pitch. Harmonic complex tones are composed of the fundamental frequency that corresponds to the repetition rate of the entire waveform. In addition, they include upper partials, harmonics (overtones) that are spaced at integer multiples of the fundamental frequency (Oxenham 2013, p. 12).

Another dichotomy of perception is successive (melodic) tones and simultaneous (harmonic) tones. Benson (2006) relates this conceptual distinction to the distinction between two types of measurements—just noticeable difference (JND), or limen, for successive tones and the discrimination threshold for simultaneous tones (Benson, 2006, pp. 11–12). However, there is some diversity of usage of these concepts.

A third dichotomy of tone perception issues is that between identification resolution and the discrimination resolution. A very well-known rule of thumb concerning working memory capacity, 7 ± 2, by Miller (1956, pp. 87–91), when applied to musical intervals, refers to the finding that resolution in single-interval absolute identification tasks is quite limited. According to Burns and Campbell (1994), subjects "are able to identify only about five to nine stimuli over the entire stimulus range with perfect consistency, or equivalently, are able to place a large number of stimuli drawn from this range into only five to nine categories without error" (p. 2704). A discrimination resolution, instead, is much more accurate. In pairwise discrimination tasks, this can mean dozens to hundreds of different stimuli that subjects are able to discriminate (Burns & Campbell, 1994, p. 2704).

Method of adjustment

One frequently used method of investigating the perception of musical intervals is the method of adjustment, where a pair of tones is presented to the participant. The first tone is fixed in frequency, and the participant can control the second one. The participant is asked to adjust the second tone to correspond to a certain musical interval. Burns (1999, p. 220) refers to Moran and Pratt (1926), who reported an average deviation of 14–22 cents when using simultaneously presented chromatic pure tones. Burns (1999, p. 220) also refers to Terhardt (1969) and Ward (1953, 1954), where simultaneous octaves composed of sinusoids produced an average standard deviation (SD) of 10 cents in repeated adjustments. Meanwhile, Burns and Campbell (1994, p. 2715) found a standard of deviation of 18.2 cents for adjustments of semitones and 20.9 cents for quarter tone adjustments.

Elliot, Platt, and Racine (1987) investigated the adjustment of successive and simultaneous intervals among musically experienced and inexperienced subjects, and the mean constant error among musically experienced subjects varied from −1 cent to +5 cents. The corresponding result among inexperienced subjects varied from −1 cent to −11 cents. Mean relative errors on six simultaneous intervals varied from 11.3 to 19.8 cents among musically experienced subjects. The corresponding values on successive intervals were 12.5–25.4 cents (Elliot et al., 1987, pp. 596–597).

Identification of intervals: Magnitude and absolute identification

The above-mentioned 7 ± 2 rule from Miller (1956) does not seem to be true for identifying the pitch of a single tone. As a highly educated professional in ear training, I know dozens of colleagues, as well as myself, who can readily identify all categories from unison to major tenth with perfect accuracy. Killam, Lorton, and Schubert (1975) also found this. They investigated the identification of harmonic and melodic intervals among musically trained students and undergraduate music students. The subjects identified chromatic intervals within an octave rather well: Overall, the percentage of identification was from 55% (major sixth) to 88% (perfect octave). The average correct identification was 77% (.2 sec) and 76% (.1 sec) (Killam et al., 1975, pp. 217–218). In the case of intervals of chromatic scale over a range of two to five semitones, category-scaling identification functions have obtained 10–20 cents of increments (Burns, 1999, p. 222). ”Relative pitch possessors can categorize frequency ratios into more than 12 categories per octave at better than chance level performance, that is, they can judge ‘out of tune’ intervals” (Burns, 1999, p. 223).

Categorical perception

Categorical perception can be defined by two attributes: well-defined identification functions and discrimination functions. Stimuli must be systematically and reliably categorized by subjects. In addition, discrimination functions have to be predicted from identification functions. Here, the assumption is that subjects cannot discriminate stimuli better than they can identify them differentially (Burns & Ward, 1978, p. 457). Categorical perception of intervals has been charted out by a few investigators (Burns & Ward, 1999; Siegel & Siegel, 1977; Zatorre & Halpern, 1979). In a study by Siegel and Siegel (1977b), a group of musicians made magnitude estimations of simultaneous musical intervals: the fourth, the tritone, and the fifth. The stimulus tones (sine-wave) were presented in increments of 20 cents. The magnitude judgments of the subjects did not follow the stimulus magnitude but rather revealed discrete steps corresponding to musical intervals of the fourth, #fourth, and fifth. In labeling tasks, the subjects produced identification functions with strictly defined boundaries: step-like estimation functions that constantly corresponded, more or less, to semitones. This happened between each of the three musical categories and was regarded by the authors as evidence for categorical perception in the pitch domain. According to the results, musicians had a clear tendency to judge out-of-tune stimuli as being in tune—within-category ratings were inaccurate and unreliable (Siegel & Siegel, 1977, pp. 402–405).

In essence, the categorical perception of intervals means, on the one hand, identification of different musical intervals in reliable category boundaries and, on the other hand, the discrimination of two stimuli only to the extent that those intervals are differentially identified (Burns, 1999, p. 226). Burns and Ward (1978) investigated categorical perception of melodic musical intervals. Musically trained listeners could almost perfectly identify five chromatic musical interval categories presented in ascending intervals as sinusoids (M2, m3, M3, p4, and triton). Discrimination thresholds were, on average, approximately 20 cents for the aforementioned intervals. For musically untrained subjects, the discrimination thresholds were much larger at 74.5 cents on average. Thus, the musically untrained observers did not show evidence of some kind of “natural” categories for musical intervals (Burns & Ward, 1978, pp. 459–466). Concerning musical intervals, Burns (1999) puts it this way: “In general, only musicians are able reliably to label musical intervals, and only musicians show evidence of categorical perception for musical intervals” (p. 229).

2.2.2 Discrimination thresholds in perception of successive tones

A number of investigations have been conducted concerning the perception of tones that are very close to each other. The majority of these studies concern pitch discrimination of successive stimuli. We will concentrate more closely on a few of them.

In the study by Spiegel and Watson (1984), frequency discrimination skills were tested among orchestral musicians and non-musicians, and the two groups were compared. The authors found a clear relationship between musical background and frequency discrimination skills. Among musicians, the median difference thresholds for single successive tones (2–8 cents) were three times smaller than the values of non-musicians (Spiegel & Watson, 1984, pp. 1690, 1694).

Schellenberg and Trehub (1994) found that changes from simple melodic patterns representing simple frequency ratios to more complex ones were more easily recognized than were changes from complex to simple ratios (p. 476). Houtsma (1968, p. 383) found that the JND defined as the 75% correct point between two successive in frequency ratios was 16 cents for several ratios in the vicinity of the octave.

Tervaniemi, Just, Koelsch, Widmann, and Schröger (2005) also investigated pitch-discrimination accuracy for defining frequency difference thresholds among musicians and non-musicians. In discrimination tasks, the stimulus frequency was 528 Hz and the deviating frequencies, presented successively, were 532 Hz (0.8%), 539 Hz (2.1%), and 550 Hz (4.2%). Musicians discriminated the pitch deviations faster and were more accurate in the task with small and medium pitch changes (0.8% and 2.1%, respectively) than non-musicians. However, even non-musicians detected pitch changes surprisingly reliably: The hit rate of non-musicians for small deviations of 0.8% (14 cents) was as high as 41.7%. Musicians detected mistuning in all conditions, and the weakest hit rate was 91.3% with small deviations of 14 cents (Tervaniemi et al., 2005, pp. 3–8). Tervaniemi and the team could perhaps have assembled one more level with a smaller deviation than 0.8%. In fact, Micheyl et al. (2006, p. 36) investigated the effects of musical and psychoacoustic training on the discrimination of successive tones. In the pre-test for the study, the discrimination threshold of musically trained participants was 0.13% in all test conditions (pure tones, complex tones, monoaural condition, and contralateral noise condition) with stimuli of 330 Hz. This corresponds to only 2 cents, which is quite low. Also, 0.13% is remarkably smaller than the results with musically untrained participants (0.86%, on average, across all test conditions, which equates to 15 cents). The difference was larger for complex tones than pure tones (Micheyl et al., 2006, pp. 39–45).

In the study by Marmel, Tillmann, and Dowling (2008), listeners discriminated slightly mistuned tones more sensitively when they were tonally more related to the context key than with tones that were tonally less related. The effect occurred only for the finer mistuning (9 cents), not for the 17-cent mistuning (Marmel et al., 2008, pp. 848–849). Zarate, Ritson, and Poeppel (2012, pp. 988–991) found that the pitch-discrimination threshold for musicians was 14 ± 3 cents at 225 Hz and 25 ± 6 cents at 475 Hz in pairs of successive tones. Another study with comparisons between successive pure tones (standard stimulus of 1000 Hz) reported a frequency discrimination threshold for musicians of 4 Hz (approximately 6 cents), and for non-musicians, the threshold was slightly under 6 Hz (approximately 10 cents) (Parbery-Clark, Skoe, Lam & Kraus, 2009, pp. 655–657).

In a study with a similar 1000 Hz standard stimulus, Strait, Kraus, Parbery-Clark, and Ashley (2010) found a mean discrimination threshold of 0.85% among musicians and 3.12% among non-musicians—this means 15 cents for musicians and 53 cents for non-musicians. A low-frequency discrimination threshold correlated with cognitive performance as measured by non-verbal IQ. This correlation was found in both groups, but the correlation was stronger among musicians than among non-musicians (Strait et al., 2010, pp. 24–25).

Schellenberg and Moreno (2010) studied the connection between musical training, pitch-processing speed, and frequency discrimination and general intelligence (*g*). In the frequency discrimination of pure tones, musically trained participants achieved better scores than did untrained participants in musically common registers (two octaves above middle C) but not in very high registers (e.g., 4000 Hz). Mean thresholds in frequency discrimination with low-frequency tasks were 18.36 cents for trained participants and 48.07 cents for untrained participants. On the high-frequency task, the thresholds of both groups increased remarkably (trained, 66.25 cents; untrained, 79.88 cents), and there was more variability within groups (Schellenberg & Moreno, 2010, pp. 214–216).

Stolzenburg (2015, p. 11) studied harmonic perception and generalized that the JND between pitches for human beings is approximately 1% for the low-frequency range that is usable for musical purposes. In musicians' language, this would be 17 cents at the pitch level of A3 (220 Hz). Further, Stolzenberg (2015) concluded that the JND can be 0.7% (equating to 12 cents) in medium and high frequencies but was clearly larger at low frequencies.

Slater, Azem, Nicol, Swedenborg, and Kraus (2017) compared professional singers, professional percussionists, and non-musicians with regard to their "signature of expertise" as musicians. Vocalists showed better scores in frequency discrimination in pure-tone thresholds and better encoding of speech harmonics compared to non-musicians. Percussionists were more precise in encoding quickly altered acoustic features of speech compared to non-musicians. In frequency discrimination tasks, the standard (pure) tone used in the test was 1000 Hz. Non-musicians could perceptually differentiate between two pitches that differed by 36 cents, corresponding to an average threshold of 2.09%. Among professional musicians, vocalists scored a mean threshold of 0.45% (8 cents) and percussionists scored 0.53% (9 cents) (Slater et al., 2017, pp. 954–960).

In general, independent of the stimuli, Ballard (2011, p. 30) assumed on the grounds of earlier findings that the difference limen for pitch perception is, in general, between 3 and 8 cents. Karrick (1998, p. 119) assumes that recognizable intonation errors could range between 2 and 20 cents. Taken all together, the above-mentioned results seem to follow these limits within a fair variance.

2.2.3 Discrimination thresholds in perception of simultaneous tones

From the point of view of the present study, it is also relevant to take an overview of discrimination results in the context of simultaneous tones. Both pure tones and complex tones have been used in previous investigations regarding this question. In this overview, I will neglect thresholds of sound pressure level (dB) and duration and reaction time and timbre.

Vos (1982) investigated the discriminability of pure and mistuned musical intervals as complex tones that were performed simultaneously. In addition, Vos studied the beat thresholds of different beat frequencies and the determination of the direction of mistuning. The results showed that discrimination thresholds are higher for major thirds than for fifths, and they are highest for the lowest beat frequencies. Further, the sensitivity to beats for mistuned fifths and major thirds was almost similar. Beat frequency seemed to influence sensitivity to beats only in some conditions. Finally, the mean identification of directional mistuning for the fifth and major third ranged from 20 to 30 cents (Vos, 1982, pp. 304, 309–312). According to Burns and Ward (1978, p. 456), the difference limen for musical interval discrimination can be estimated from the SD of repeated adjustments being in the range of 10 to 30 cents.

Elliot et al. (1987) investigated the adjustment of simultaneous intervals among musically experienced and inexperienced subjects. Mean relative errors on six simultaneous intervals varied from 11.3 to 19.8 cents among musically experienced subjects and from 18.1 to 23.3 cents for musically untrained subjects (Elliot et al., 1987, pp. 596–597).

Burns (1999) wrote that ”for simultaneous intervals composed of two complex tones with many harmonics, subjects can easily distinguish on this basis intervals mistuned from exact small-integer ratios by as little as ±2 cents” (p. 245). However, the deviation of simultaneous low-level pure tones can raise the threshold up to 50 cents. In summary, participants can use beats and roughness connected to sensory dissonance of intervals to discriminate small mistunings, especially in the case of typical musical instruments with rich harmonic spectra (Burns, 1999, p. 245).

The above-mentioned studies show a wide range of discrimination thresholds for simultaneous tones. Moreover, there seems to be a lack of investigations addressing the perception of mistuned harmonic chords. Experiment 1 with harmonic mistunings fills this gap. Dunnigan (2002, p. 81) argued that identification of a note error seems to be a different task from the accurate discrimination of a note being sharp or flat. In the following sub-chapter, we concentrate on the latter phenomenon.

2.2.4 Perception of horizontal mistuning

The following paragraphs introduce investigations where the perception of horizontal mistunings among melodic intervals or in melodies of musical excerpts were in focus.

Dobbins and Cuddy (1982) investigated the "discrimination of octave" finding support of the phenomenon called "octave stretch." The stimulus tones were sinusoidal, with the manipulated octaves presented linearly, and the participants used the method of adjustment. The results showed that the subject's estimated octave was approximately 22 cents sharper than the physical octave (1200 cents). The differences between subjects were rather large, from −2.43 cents up to 34.25 cents (Dobbins & Cuddy, 1982, pp. 412–413).

Schellenberg (2001) studied musically trained and non-trained listeners who were tested on their ability to discriminate pure-tone intervals belonging to the perfect fifth category of an equally tempered fifth of 700 cents. Other fifths were mistuned at 660, 680, 720, and 740 cents. The intervals to be compared were presented in both sequential (melodic) and simultaneous (harmonic) conditions. Participants succeeded in discriminating better when the standard interval was more in tune than the comparison interval. When the standard interval was less accurately tuned than the comparison interval, remarkably poorer scores were observed. The results of the trained listeners were significantly better than the performance of the untrained listeners, and a significant correlation was found between musical training and discrimination of flat intervals (Schellenberg, 2001, pp. 232–241). The size of differences, 20 cents, is close to the syntonic comma (21.51 cents) used in this research.

Vurma and Ross (2006) asked 13 professional singers to perform a series of melodic intervals, a minor second, a tritone, and a perfect fifth, both ascending and descending. Listeners—both the participants themselves and other participants—were asked to listen to the performance and estimate whether each interval was tuned correctly. For the intervals judged to be in tune, the average deviation compared to just intonation intervals was 11 cents. In some cases, melodic intervals could be accepted as correctly tuned even when they were 20–25 cents out of tune (Vurma & Ross, 2006, pp. 331–342).

Tonal expectations can influence pitch perception, as shown by Marmel et al. (2008) when, using short melodies, participants judged the pitch of tonally related tones more accurately than the pitch of less related target tones. This occurred even if participants judged tonally related targets more in tune overall. Mistunings in melodies were 17 and 35 cents (Marmel et al., 2008, pp. 843–849).

Vurma (2010) studied the pitch-matching strategy of singers in two-part a cappella singing in reaction to pitch deviations of equally tempered values on the ensemble partner's part. Most singers preferred equally tempered melodic intervals in their own part, while they usually ignored the mistuning (20 and 40 cents) in vertical intervals. Hence, they followed the preciseness of melodic intervals to that of harmonic intervals in the accompaniment part and ignored the harmonic mistuning between their part and the synthesized accompaniment. In a perception task, the participants recognized 58% of 40 cent mistunings and 34% of 20 cent mistunings in the accompaniment part (Vurma, 2010, pp. 27–28). Vurma (2010, p. 32) speculated that the result would have been different if the singers had been asked to follow the purity of harmonic intervals for accompaniment with all those modifications. For the present research, it is relevant to note that the latter mistuning is close to the syntonic comma (21.51 cents). In the experiment by Vurma (2010), there were mistunings of 40 cents and 20 cents. These mistunings seem arbitrary, but 20 cents is near the syntonic comma, and 40 cents is very close to the diminished second (16:15 × 25:24 = 128:125 = 41.059 cents).

Van Besouw, Brereton, and Howard (2008) studied the range of acceptable tones (RAT) for those with vibrato and those without vibrato, using repeating ascending and descending three-tone arpeggios. The RAT varied from 21.9 cents to 37.55 cents and was approximately 10 cents greater (30–36 cents) for vibrato tones than for unmodulated tones (21–25 cents). The interesting detail is that in just intonation, the lower RAT limit in major thirds was 1.5 cents wider than the upper tone of the M3 interval in just intonation (386 cents). The upper RAT limit was 6.5 cents wider than M3 in Pythagorean tuning (408 cents). Yet, widening of M3 does not seem to alter the results. In perfect fifths, 686 was the lower RAT limit. Sharp perfect fifths were not accepted because the upper RAT limit was 710 cents (van Besouw et al., 2008, pp. 147–152).

Hedden and Baker (2010) investigated children's singing accuracy with a familiar melody, both accompanied by a piano and a cappella. One observation in perceptual analysis was that the expert judges did not judge pure a cappella singing as being pure. Instead, the acoustic and perceptual analyses were parallel when judging out-of-tune singing with accompaniment (Hedden & Baker, 2010, pp. 42–44).

Larrouy-Maestri (2018) studied the perception of mistuning with a method called the "limits procedure." The subjects were asked to identify sung manipulated six-tone melodies as in tune or out of tune. The measured tolerance for mistuning was approximately 25 cents and varied from 10 cents to 50 cents. Concerning the subjects' tolerance with regard to mistuning across six-tone melodies, the mean tolerance threshold was approximately 21 cents. Music experts showed smaller thresholds (10 cents) than lay listeners (25 cents) (Larrouy-Maestri, 2018, pp. 6–9).

2.2.5 Perception of vertical mistuning

This sub-chapter introduces investigations in which the perception of vertical mistunings was the focus. It is a question of perception of mistuned simultaneous intervals or chords in harmonic musical excerpts.

Zatorre and Halpern (1979) investigated the perception of major and minor thirds of simultaneously sounded pure tones. Musicians judged 300, 314, 329, and mostly 342 cent intervals as a minor third. Respectively, intervals of 400, 386, and mostly 371 cents were judged as major thirds (Zatorre & Halpern, 1979, pp. 386–387).

In a study by Hall and Hess (1984), the identification threshold of mistuning of simultaneous musical intervals was mostly between 15 and 30 cents. The authors had only seven subjects, and the results varied among them with regard to intervals. The mistuning was hardest to detect in minor seventh and tritone intervals. Further, just intonation intervals were judged more in tune than equally tempered intervals (Hall & Hess, 1984, pp. 175–177, 191).

Rasch (1985) investigated the perception of melodic and harmonic intonation in two-part musical fragments. The melody was intonated in equal temperament, while the harmonic intervals were justly intonated. In addition to this "correct" intonation, he used mistuning factors with weighted mean values of 6.6 cents, 16.6 cents, and 33.1 cents. Rasch (1985) found that the larger the size of the mistuning, the poorer the samples were judged. Surprisingly, the mistuning factor of 6.6 cents was preferred over the correctly tuned one. Mistuning in the melodic line was experienced as most disturbing, and mistuning in the bass part was least disturbing. Mistuning of 16.6 cents (weighted mean) in harmonic intonation was more often experienced as being out of tune than in tune. The last category of 33.1 cents with harmonic mistuning was judged out of tune by nearly all the participants (Rasch, 1985, pp. 446–448).

Not surprisingly, musical expertise affects the discrimination of vertical mistunings. Koelsch, Schröger, and Tervaniemi (1999) investigated the pitch-discrimination accuracy of professional violinists and non-musicians. The standard stimulus involved major triads of sinusoidal tones, including a pure major third and a perfect fifth. The comparison triad had its third lowered from 495 Hz to 491.25 Hz, which corresponds to 12 cents. Violin players recognized 80% of the mistuned triads, and non-musicians only recognized 10% (Koelsch et al., 1999, pp. 1310–1313). If the reported hertz values hold true, the stimulus triad was, in fact, not pure but had a relatively large fifth (708 cents). This presumably could have affected the results.

In the aforementioned study by Schellenberg (2001), musically trained and non-trained listeners were tested on their ability to discriminate pure-tone intervals belonging to the perfect fifth category of equally tempered fifths of 700 cents. With regard to harmonic intervals, in Schellenberg's study, musically trained participants had clearly better performance than untrained participants only in flat intervals. For sharp intervals, there were no differences between groups (Schellenberg, 2001, p. 244).

Dunnigan (2002) found that college music majors identified intonation errors significantly more accurately than college non-music majors and high school students. Dunnigan used equally tempered tonic chords in a perception task. Sharp thirds were easier to perceive than flat thirds, and sharp roots and fifths of a tonic chord were harder to perceive than flat roots and fifths (Dunningan 2002, pp. 145–146).

Vurma (2010, pp. 27–28) found that 22% of his participants correctly judged a tuned accompaniment to be flat and 24% judged it to be sharp. Indeed, it should be remembered that even octaves are more easily accepted as somewhat stretched (+ 10–17 cents), although horizontally performed, than theoretically pure versions (Sundberg, 1982, pp. 64–71, 75–76). Also, Hartmann (1993, pp. 3403–3405) investigated octave stretch with successive sine tones involving octaves mistuned by 11, 23, and 34 cents. Listeners' matching reproducibility showed an average SD of 8.6 cents, while the largest of the SDs was 19.6 cents.

Larrouy-Maestri, Harrison, and Müllensiefen (2019) introduced an adaptive test of mistuning perception ability. Excerpts of pop music performances were assembled as stimulus material involving a pitch-manipulated vocal track. Another validation study applied this test to 66 subjects with great amounts of experience and musical expertise to produce evidence of the reliability and validity of the test. At the conclusion of this test, the authors stated that it is a capable experimental tool for testing human ability to judge mistuning (Larrouy-Maestri et al., 2019).

2.2.6 Perception and intonation in performance

The important 20th century tuning theorist J. Murray Barbour (1951/2004) was not convinced that singers can sing thirds and sixths purely without beats because he thought that the human ear has no affinity for justly tuned intervals. He was skeptical of singers' ability to perceive errors in the range of the syntonic comma (21.5 cents) (1951/2004, pp. 196–198). However, as the following brief review will show, musicians can often make smaller perceptual distinctions than they are able to show in their own performance intonations.

Yarbrough et al. (1995) studied tuning performance and perception of young instrumentalists and found no correlation between performance and perception in terms of cent deviation scores, which corroborates earlier findings. The direction of original mistuning affected the direction of the errors for both performance tasks (tuning F or Bb with their own instrument) and perception (tuning knob of a variable-pitch keyboard). In the performance task, approaching the target pitch from above resulted in sharper responses; approaching it from below resulted in flatter responses. Mechanical limits of wind instruments affected intonation more than the perception of intonation (Yarbrough et al., 1995, pp. 237–240).

Again, Morrison (2000, pp. 47–50) noticed that melodic context did not seem to affect the accuracy of wind players, and the pitch accuracy demonstrated within a musical context only had a weak connection to the ability of a performer to tune an isolated pitch. Also, in the study by Worthy (2000, p. 232), only a low correlation was found between perception and performance responses. Bradshaw and McHenry (2005) studied pitch discrimination and pitch production of inaccurate adult singers. They also did not find a statistically significant relationship between pitch-discrimination and pitch-matching skills. Some singers discriminated both pitches and produced pitches inaccurately. The second group consisted of singers who discriminated pitches accurately but produced pitches inaccurately. Reasons for this might be a lack of experience or an inflexible vocal mechanism that is difficult to coordinate. The investigators emphasized that music teachers should notice this characteristic (Bradshaw & McHenry, 2005, pp. 436–439).

In Dunnigan's (2002) study, clarinet players tended to play the root and the fifth of tonic chord sharp, whereas the third was usually played slightly flat. Slow tempo was connected to sharp intonation. They also performed significantly sharper melodies in the descending melodic directions than with ascending directions (Dunnigan, 2002, pp. 145–146). It is no wonder that clarinet players tended to play thirds a bit flat. The third in just intonation is 386 cents and equally tempered is 400 cents. Perhaps the players were aiming to beat minimization in thirds. If the roots and the fifths were played sharp and the thirds slightly flat, the relationships between intervals are close to just intonation intervals. Kopiez (2003, p. 407) wrote, "A certain degree of dependence of the melody on the harmonic progressions is necessary for successful intonation adaptation."

Ballard (2011) studied the perceived intonation and performance intonation by undergraduate wind instrument majors and compared it with just intonation, equal temperament, and Pythagorean tuning. The accompaniment was executed with those three tunings. No significant correlations with any single tuning system were found, although equal temperament had some advantages in performance. Again, there was no correlation between perceived intonation and performed intonation, nor was there a correlation between participants' vocal and instrumental performances. The participants intonated better (correct responses 68%) in comparison to their performance in perception (47%). In addition, the instrumental task produced lower deviations (from 7.36 to 9.64 cents) than the vocal task (deviations from 16.80 to 23.47 cents) (Ballard, 2011, pp. 24–30). On the basis of Ballard's study and the other reviewed studies, it seems that intonation perception and intonation performance are not strongly connected. Powell (2010, p. 91) crystallizes the idea, saying, "Intonation perception and intonation performance may be discrete abilities."

2.2.7 Effects of vibrato and timbre

Vibrato and timbre and their influence on intonation have been in focus in several investigations. They are mostly connected to musical practices. I will introduce a few studies of them.

Vibrato and masking

In a study of violinists' and cellists' use of vibrato, Geringer and Allen (2004, pp. 167, 173–176) found that the use of vibrato increased the stability of a performer's intonation. The previous result is in line with Morrison and Fyk (2002, p. 189), who wrote, “The presence of vibrato in a target stimulus has also been found to affect the accuracy of pitch responses.”

String instrument vibrato was the attraction in a study by MacLeod (2008), as well. Among university and high school violin and viola players, pitch register affected the vibrato rates and widths. The findings were surprising: mean vibrato width was 34 cents in the lower register and 58 cents in the upper register, and vibratos were wider when performing forte passages as compared with piano passages (MacLeod, 2008, pp. 52–53); 58 cents sounds like a lot, indeed.

Pope (2012) investigated the influence of playing position, fingers used, and level of training on vibrato, and playing position had a significant impact on vibrato rates, widths, and pitch with both vibrated and non-vibrated tones. The mean vibrato width for cellists was 32.51 cents. Vibrato oscillation patterns were found both above and below the note (Pope, 2012, pp. 60–61). Mick (2014) found convergent results regarding double bass players’ vibrato width. Total vibrato widths ranged from 7 to 55 cents. Vibrato widths increased consecutively with higher pitch registers or positions. For all fingers, vibrato width was increased by multiple cents in consecutively higher positions. The pitch matching of vibrato tones was almost exact with non-vibrated tones (Mick, 2014, pp. 50–52).

Interestingly, van Besouw et al. (2008) noticed that vibrato tone can be 10 cents flat before it is perceived as being out of tune. However, in the study by Geringer, MacLeod, and Ellis (2014), the pitches of vibrato tones on the violin were perceived as significantly (2–5 cents) lower than corresponding tones without vibrato. Among experienced players, the differences were smaller than among less experienced players. In a performance task, the participants were asked to tune their own instrument to match stimulus tones. The responses with vibrato were a few cents lower than the responses without vibrato (Geringer et al., 2014, pp. 359–361).

Cello and violin sounds were also used in the study by Geringer, MacLeod, and Allen (2010), in which string performers and music majors (without string performance experience) were asked to adjust to match the perceived pitch of vibrato stimuli. The distribution of scores produced a significant difference between the two groups: For violin and cello tones, the string performers exhibited a smaller deviation in tuning estimations than non-string players. Listeners apparently perceive the intended and performed pitch as a mean of the performed vibrato extents (Geringer et al., 2010, pp. 354, 359–361).

Using vibrato can make intonation more indistinct. Among others, Sundberg (1982, p. 76) thinks that the vibrato in Western repertoire is an essential means to reduce the risk for beats in pitch matching: With vibrato, pitches that deviate from theoretical values are better accepted by listeners than are pitches without vibrato. Bohrer (2002) argued outright that it is a misunderstanding to assume that vibrato should always be present in musical practice: Vibrato has the capacity of turning beat detection inoperative because vibrato disguises beats; vibrato singers and non-vibrato singers use different tools to develop their intonation control, and the masking effect covers the harmonics in all articulated vowels (Bohrer, 2002, pp. 40–41). In a related manner, Duffin (2008) argued that constant vibrato in musical performance can be related to the generalization of equal temperament. He wondered if performers' sensation of the vibrato masks the unpleasantness of equally tempered thirds. However, during the periods when non-equal temperaments were used, vibrato was used as an ornament (Duffin, 2008, pp. 158–159). Van Besouw et al. (2008, p. 145) noted, "It is widely believed that vibrato, a musical device consisting primarily of a modulation in frequency, can be used to disguise errors in tuning."

The influence of tone quality on pitch perception

The influence of timbre on intonation has been observed from several aspects: tone quality of wind instruments related to intonation ratings, effects of changes in tone quality on the perception of interval size, influences of tone quality with instrument and singing voice intonation, and the influence of timbre on perceived interval size.

Geringer and Worthy (1999) investigated the effect of tone quality on intonation ratings with clarinet, trumpet, and trombone stimuli. Non-majors and high school students had a sharp tendency in their intonation ratings when there were changes of tone quality in the bright direction. Intonation by clarinet with tone quality changes in the bright direction was judged sharper than intonation by trumpet and trombone. Contrary to the high intonation judgments accompanying changes of tone quality in the bright direction, the stimuli with darker tone quality were judged as flatter in intonation (Geringer & Worthy, 1999, pp. 142–147). Worthy (2000, p. 231) also found that the participants combined "bright" tone quality with sharp tuning and the "dark" tone quality with flat tuning.

Further, Russo and Thompson (2005) found that for musically untrained participants, timbre had an influence on the perceived size of melodic intervals. The six-semitone interval changes were manipulated with congruent timbre change, which means that an ascending interval involves a shift from a dull to a bright timbre, and this was perceived to be larger than the seven-semitone interval with an incongruent timbre change (ascending interval involving a shift from bright to a dull timbre). Russo and Thompson called this an interval illusion. In addition, musically trained participants were sensitive to the effect of timbre on perceived interval size, especially for descending pitch intervals. To summarize, pitch and timbre are not perceived independently (Russo & Thompson, 2005, pp. 565–567).

Vurma, Raju, and Kuuda (2011) noticed that the differences in timbre in musical instruments affected assessments of the pitch of sound played on one instrument in relation to the pitch of a sound played on another instrument. In their test, the participants were asked to rate two consecutive sounds as being in tune, flat, or sharp. In comparisons between sounds having different timbres, the brighter sounds of a trumpet and a professional opera tenor were most often perceived as being in tune with a duller viola sound when the latter was 15–20 cents higher than the brighter sounds (Vurma et al., 2011, pp. 298–304).

According to Hutchins, Roquet, and Peretz (2012), *vocal generosity* is a phenomenon where listeners more easily accept tuning errors performed by singing voice than they do performances with other timbres. This effect seems to occur in small tuning deviations (10–30 cents), which in singing were consistently judged as being in tune. Vocal pitches needed around 50 cents of mistuning on average to be deemed out of tune. Violin pitches mistuned about 50 cents were judged as a fundamentally different note, while the corresponding limit for vocal timbre was 90 cents (Hutchins et al., 2012, pp. 155–158). These results are startling but somehow make sense. An incredible amount of mistuning is tolerated in performances by classical singers all the time.

2.2.8 Synopsis of previous research on recognition of mistuning

In previous investigations concerning intonation perception, the main focus has often been on separate intervals and chords in melodic contexts. The pitch discrimination related to vibrato has also been charted quite thoroughly, and the pitch of vibrato tone is perceived as flatter than a non-vibrated tone. Timbre affects pitch discrimination in many ways. An ability with pitch discrimination does not necessarily correlate with ability in pitch matching and performance. A musician can be capable of proper intonation independent of pitch discrimination skills. The intonation errors of a singing voice are more acceptable than other voice sources. Table 8 provides a synopsis of previous research on the recognition of mistuning.

Table 8. Synopsis of previous research on recognition of mistuning.

Theorem	More exactly	Reference
Thresholds in simultaneous tones varied considerably.	The thresholds for simultaneous tones can vary from 2 cents (complex tones) to 50 cents (low-level pure tones).	Burns (1999)
	Relative errors on adjusting six simultaneous intervals varied from 11.3 to 19.8 cents among musically experienced subjects and from 18.1 to 23.3 cents for musically untrained subjects.	Elliot et al. (1987)
Thresholds between 2 cents and 19 cents for musicians in successive tones.	The median difference thresholds for single successive tones (2–8 cents) were three times smaller among musicians than the values of non-musicians. They can vary from 2 cents to 19 cents among professional musicians.	Spiegel & Watson (1984)
	A threshold of 12 cents for musicians, which is the average level of this review.	Tervaniemi et al. (2005)
	The discrimination thresholds of musically trained participants were only 2 cents in all test conditions, while non-musicians had a threshold of 13 cents.	Micheyl et al. (2006)
	A mean threshold for musicians of approximately 6 cents and approximately 10 cents for non-musicians.	Parbery-Clark et al. (2009)
	The mean thresholds in frequency discrimination were 18.36 cents for musically trained participants and 48.07 cents for musically untrained participants on a low-frequency task (the lower tone being 400 Hz).	Schellenberg & Moreno (2010)
	A mean threshold of 15 cents among musicians and 53 cents among non-musicians.	Strait et al. (2010)

Theorem	More exactly	Reference
	The pitch-discrimination thresholds for musicians were 14 ± 3 cents at 225 Hz and 25 ± 6 cents at 475 Hz in pairs of successive tones.	Zarate et al. (2012)
	Professional vocalists scored a mean threshold of 8 cents in frequency discrimination, while percussionists had 9 cents, and non-musicians had 36 cents.	Slater et al. (2018)
	In general, a good mnemonic could be “The difference limen for pitch perception is between 3 and 8 cents.”	Ballard (2011)
None of the mistunings were detected.	Professional singers recognized 58% of 40 cent mistuning of the accompaniment part, 34% of 20 cents mistuning.	Vurma (2010)
	In the study, professional violinists detected 80% of mistuning (−12 cents in the third of the major triad), while non-musicians detected only 10%.	Koelsch et al. (1999)
	In the task of relative pitch (detecting mistuning from two familiar melodies), musically trained scored a mean threshold of 41.63 cents and 43.92 cents. Put into perspective of discrimination thresholds, the mistuning of over 40 cents seems large.	Schellenberg & Moreno (2010)
	Detectable intonation differences could range between 2 and 20 cents.	Karrick (1998)

Theorem	More exactly	Reference
	The measured tolerance concerning the subjects' tolerance with regard to mistuning across six-tone melodies, the mean tolerance threshold was approximately 21 cents. Music experts showed smaller thresholds (10 cents) than lay listeners (25 cents).	Larrouy-Maestri (2018)
The acceptance of sharp octave and major thirds vs. flat fifths.	Stretched octaves (+15 cents or more) were better accepted than the theoretically pure octave among concert singers.	Sundberg (1982); Hartmann (1993)
	The subject's estimated octave was approximately 22 cents sharper than the physical octave (1200 cents).	Dobbins & Cuddy (1982)
	Flat fifths were easier to accept than sharp fifths.	Schellenberg (2001); Dunnigan (2002)
	The range of acceptable tones (RAT) limits in major thirds was 1.5 cents wider than the upper tone of the M3 interval in just intonation (386 cents). The upper RAT limit was 6.5 cents wider than M3 in Pythagorean tuning (408 cents).	Van Besouw et al. (2008)
There was difficulty in recognizing correct intonation.	23% of samples were musically accurate, but the subjects judged up to 63%: Musicians had a clear tendency to judge out-of-tune stimuli as in tune.	Siegel & Siegel (1979)
	Mistuning factor of 6.6 cents was preferred over the correct one.	Rasch (1985)
	Expert listeners may judge mistuned melodic intervals (20 to 25 cents out of tune) as correctly tuned.	Vurma & Ross (2006)

Theorem	More exactly	Reference
	Participants did not judge pure a cappella singing as being pure. In addition, listeners judged perception-based a cappella singing to be more in tune than singing with accompaniment, although acoustic analysis revealed that there were no significant differences between those two groups.	Hedden & Baker (2010)
	When the pitch of the accompaniment part has no deviation at all (correctly tuned), 22% judged it to be flat, and 24% judged it to be high.	Vurma (2010)
	Vibrato tone can be 10 cents flat before it is perceived as being out of tune.	Van Besouw et al. (2008)
	Sharp thirds were easier to perceive than flat thirds. Indeed, this is a matter of mystery in some respects.	Vurma (2010)
Musical experience increases pitch-discriminating skills.	From the music educator's point of view, it is comforting to verify the training: Musically trained participants perform more successfully in frequency discrimination tasks than musically untrained participants.	Spiegel & Watson (1984); Koelsch et al. (1999); Dunnigan (2002); Tervaniemi et al. (2005); Micheyl et al. (2006); Parbery-Clark et al. (2009); Strait et al. (2010); Schellenberg & Moreno (2010); Slater et al. (2018)
Going out of tune is more conspicuous than going in tune.	When the standard interval was better tuned than the comparison interval (e.g., 680–660 cents), the listeners discriminated a pair of intervals better. When the standard interval was less accurately tuned than the comparison interval, a remarkably poorer score was observed.	Schellenberg (2001)

Theorem	More exactly	Reference
Note error vs. accurate discrimination.	In the present research, the following point is essential: Identification of a note error seems to be a different task than an accurate discrimination of note being sharp of flat.	Dunnigan (2002)
Tonality and direction of mistuning are related to pitch perception.	The following aspect is pursued to eliminate from the experiments of this book: Tonally related targets were discriminated more sensitively than tonally less related targets.	Marmel et al. (2008)
	Direction of original mistuning significantly affected the direction of the errors for both performance tasks and perception.	Yarbrough et al. (1995)
Pitch discrimination does not seem to depend on the tuning system.	No significant correlation was found to any tuning system (just intonation, equal temperament, Pythagorean tuning) for melodic pitch perception.	Ballard (2011)
Good pitch discrimination skills do not guarantee accurate performance.	Pitch-matching accuracy and pitch perception ability do not seem to be related.	Yarbrough et al. (1995); Kopiez (2003); Bradshaw & McHenry (2005); Powell (2010); Vurma (2010); Ballard (2011)
	Only a low correlation between perception and performance responses.	Morrison (2000); Worthy (2000)
	Inaccurate singers could be divided into two groups: A) singers, who discriminated pitches and produced pitches inaccurately, and B) singers, who discriminated pitches accurately but produced pitches inaccurately.	Bradshaw & McHenry (2005)
Vibrato widths vary, with long ranges above and below the stimulus.	Vibrato widths seem to vary between 30–60 cents among string players, more in high register, less in low register. Oscillation patterns divided above and below a note.	Geringer & Allen (2004); MacLeod (2008); Pope (2012); Mick (2014)

Theorem	More exactly	Reference
String instrumentalists recognize well the pitch of vibrated tones.	String instrumentalists and music majors (no string performance experience) perceived the pitch of vibrato tones very close to the center of the vibrato both for violin and cello tones. String players exhibited a smaller deviation than non-string players.	Geringer et al. (2010)
The pitches of vibrated tones are perceived as flatter than tones without vibrato.	Vibrato tone can be 10 cents flat before it is perceived as being out of tune, which is quite small compared with the extent of vibrato used, which was even +/-70 cents.	Van Besouw et al. (2008)
	The pitches of vibrato tones, played by violin, were perceived significantly (2–5 cents lower) than corresponding tones without vibrato.	Geringer et al. (2014)
Vibrato masks intonation errors.	It is a misunderstanding to assume that vibrato should always be present in musical practice.	Bohrer (2002)
	Range of acceptable tones (RAT) among six professional musicians varied from 21.9 cents to 37.55 cents when the participant was asked to give in-tune and out-of-tune judgments for vibrated and non-vibrated tones. The RAT for vibrato tone was around 10 cents greater than for non-vibrated tones.	Van Besouw et al. (2008)
Tone quality influences pitch perception.	Intonation by clarinet with tone quality changes in bright direction was judged sharper than intonation by trumpet and trombone.	Geringer & Worthy (1999)
	Participants combine “bright” tone quality with sharp tuning and the “dark” intonation with flat tuning.	Geringer & Worthy (1999); Worthy (2000)

Theorem	More exactly	Reference
	“Interval illusion” exists when an internal interval involves a shift from a dull to a bright timbre; as a result, the interval is perceived as larger.	Russo & Thompson (2005)
	Trumpet sound and professional opera singer sound (tenor), which are bright in timbre, were perceived as 15–20 cents higher than viola sound (dull timbre). The maximum number of ”in-tune” ratings was given for the voice that was 15–20 cents lower than the reference sound.	Vurma et al. (2011)
Vocal generosity is noticeable.	Singing performances were judged in tune or out of tune. The average deviations were 11 cents for those intervals judged as in tune. For those intervals judged as out of tune, the average deviations were 25 cents. Melodic intervals were accepted as correctly tuned even when they were 20–25 cents out of tune.	Vurma & Ross (2006)
	The vocal generosity effect is a phenomenon in which listeners accept tuning errors performed by singing voice more than performances by another timbre. This effect seems to occur in small tuning deviations (10–30 cents), which are consistently judged as being in tune. Vocal tones need around 50 cents of mistuning on average to be estimated as out of tune (violin tone, 30 cents). Violin pitches mistuned about 50 cents were judged as a fundamentally different note. The corresponding number for vocal tone was 90 cents.	Hutchins et al. (2012)

Formatting Experiment 1

Previous investigations of frequency discrimination thresholds, perception of intervals, and chords with several factors influencing pitch discrimination showed that recognition of mistuning of 21.51 cents (81:80), the syntonic comma, is worth exploring. The size of deviation is suitable: Thresholds for pitch discrimination in cents vary from 2 up to 20 among professionals in a harmonic context. The perceived mistunings used in previous studies have ranged from 10 cents to dozens of cents. In this research, the focus is not on investigating the threshold of perception of intonation errors, nor it is not meaningful to investigate participants' reactions to different sizes (in cents) of errors. The problem with just intonation is that apart from 'just' intervals, it also produces a set of mistuned intervals. From the approach of four-part harmony in Western tradition, the unavoidable discrepancy of just intonation is the syntonic comma, which sets boundaries on the intonation of musical intervals in real musical contexts, and a conflict of pure major thirds and the pure fifth produces a discrepancy of 21.51 (21.506) cents (Paret & Sibony, 2017, p. 79).

In Experiment 1 (discussed in Chapter 3), the target triad is, as mentioned earlier, the second-degree minor triad with the minor third of 32:27 and the perfect fifth of 40:27. Both were judged as unpleasant and out of tune in the baroque era, and both were judged as unsatisfying hundreds of years ago as well (Barbour, 1938, p. 49). Hence, this interpretation of the mistuned triad is very traditional. On the other hand, the fifth of the mistuned second-degree minor triad (ii triad) is 680.45 cents in the present study, which is practically the same as the standard and comparison intervals of 680 cents in Schellenberg's (2001) study. In addition, recent investigations of the perception of mistuning and pitch discrimination thresholds have highlighted that a deviation of 21.51 cents can be judged as mistuned.

The syntonic comma and its discrepancies with the intonation in tonal texture are not very well known in music education and the instrumental pedagogy of our time. Throughout the history of Western music, there have been countless attempts to avoid the syntonic comma in practical applications of intonation. Now, after 150 years of dominance by equal temperament, it seems reasonable to investigate whether young music learners, on the whole, recognize this mistuning among pure triads of just intonation.

On the grounds of previous investigations, it can be assumed that the mistuning of 21.51 cents is possible to detect for the pupils and students in music-intensive classes. There are also reasons to expect that the majority of participants should recognize a mistuning of this size. Yet a corresponding empirical study has not, to the best of my knowledge, been done before now.

2.3 Intonation preferences: Previous research

This sub-chapter presents an overview of research findings related to intonation in musical performance. Pitch matching in musical performance has been the subject of a variety of investigations. The ability to perform with error-free accuracy is an important aim for musicians and music educators (Schlegel & Springer, 2018, p. 394). First, I will review previous research on intonation in performance with various musical instruments. Second, I will go through some studies concerning the judgments and preferences of different aspects of intonation. Third, the concept of pitch drift has been the subject of some recent investigations, mainly as regards the performance of singing groups. There are no earlier studies, to my experience, where pitch drift would have been offered as a preferred choice of intonation system.

2.3.1 Intonation in performance

Intonation in performance is affected by several aspects. One remarkable factor is simply the instrument group. I will introduce some earlier findings regarding the intonation issues of different instrument groups, starting with string instruments.

Intonation by string instrumentalists

Measuring intonation by a string trio, Sundberg (1982) noted that the intervals played were rather close to equally tempered intervals, but often slightly larger. A part of these values was close to the Pythagorean values (Sundberg, 1982, p. 54). Kantorski (1986) studied the intonation of college-aged string instrumentalists playing ascending and descending whole-tone tetrachords with different accompaniment intervals and compared them to equal temperament. The results showed an overall tendency toward sharpness. Playing in the upper register (with accompaniment below), the deviations from equal temperament were larger than while playing in lower registers (with accompaniment above). Both were sharp in intonation compared with equal temperament (from 42.2 cents up to 75.4 cents). The intonation of thirds produced the largest deviations in both the lower and upper registers. The deviation range of bassists was larger than other string players (Kantorski, 1986, pp. 200–208). The measured sharpness of intonation in Kantorski's study seems large, but it is in line with my ordinary observations. For example, the justly intonated major third of vertical major triad may feel odd to string players.

Fyk (1995) investigated intonation by violinists in several experiments with Paganini's *Theme and Variations V*; the measured deviations were largest compared with just intonation and smallest compared with Pythagorean tuning. Melodic major thirds were very sharply tuned (up to 413 cents), and minor seconds were narrow (mostly under 90 cents), which means a close correlation with Pythagorean tuning (Fyk, 1995, pp. 110–190). This is in line with Bohrer (2002, p. 5), who claims that musicians, in general, tend to sharpen higher notes and flatten lower notes, meaning interval stretching, which could be associated with expressive intonation.

A sharp tendency might be derived from rehearsing Pythagorean scales with large thirds and narrow semitones. Basically, it could be partly a question of string instrument pedagogy.

Intonation by wind instrumentalists

Duke (1985) studied wind instrumentalists' intonational performance. Participants played major third, perfect fourth, perfect fifth, and major sixth melodically and harmonically. Melodic intervals were narrowed when performed in an ascending direction and expanded when performed in a descending direction. Junior high school participants tended to play sharp in relation to equally tempered intervals. College wind players evidenced a slight tendency toward flat intonation (Duke, 1985, pp. 108–110). Duke's results generate a sentiment where narrow ascending intervals connected to expanding descending intervals lead to a downward pitch drift.

Karrick (1998) studied intonation by wind instrumentalists (advanced students and professional musicians). The participants were asked to play a duet with computer-based oboe sound without vibrato in a two-part adaptation of the chorale *O Haupt voll Blut und Wunden* (BWV 244) by J.S. Bach. The deviations were largest compared with just intonation and smallest compared with equal temperament. The out-of-tune pitches usually deviated in the direction of sharpness. Thirds and sixths deviated more from equal temperament than octaves, fifths, and fourths (Karrick, 1998, pp. 112–125). Morrison (2000) studied young players' (experience 1–7 years) intonation of a short melody, and a tendency for sharp intonation was found among the experienced players (Morrison, 2000, pp. 47–48).

Kopiez (2003) studied musicians' adaptability to tuning systems. Professional trumpet players were asked to play, in realistic conditions, the top voice of a chorale in 5-limit just intonation and equal temperament. The results showed that the musicians could not adapt their playing to just intonation. The average deviations were 4.8 cents (SD = 6.5 cents) when the players were asked to play in equal temperament and 6.7 cents (SD = 8.1 cents) in 5-limit just intonation. An overall tendency toward higher pitched intonation was found. In particular, harmonic major thirds were intonated sharp in both tunings. In just intonation, the deviations in major thirds were always upward (from 5.6 cents to 23.1 cents), while the minor thirds were slightly narrowed. The greater adaptability to equal temperament suggests that exposure to equally tempered piano very early in instrumental lessons might cause a "burn-in-effect" (Kopiez, 2003, pp. 383–407). Interestingly, in just intonation, the melodic line in Kopiez's example would include six syntonic commas. In addition, the dominant seventh chords include syntonic commas in harmonic intervals. This piece of music cannot be intonated in just intonation without tempering certain intervals with a syntonic comma. In an email (personal communication, January 19, 2014), Kopiez advised that the problem was solved in his experiment with an adaptive approach. Only the harmonic intervals were based on just intonation; the chord roots defined the vertical tuning. Hence, chromatic steps in the bass line were compromised, and they were played in equal temperament.

Leukel and Stoffer (2004) studied intonation by professional flautists in simultaneous intervals (major triad, minor triad, diminished triad, and dominant seventh chord) in different harmonic contexts. Major thirds were intonated very close to just intonation and minor thirds close to equal temperament, practically independently of harmonic context. Pythagorean tuning seemed not to be a reference system at any chords intonated in this experiment (Leukel & Stoffer, 2004, pp. 84–86). These results were somewhat contrary to the results of previous studies mentioned. I have found in several conducting situations that brass instrumentalists, in particular, can learn aim to pure vertical intervals in harmonic context if they are guided the right way.

Byo, Schlegel, and Clark (2011) summarized previous investigations on intonation in performance, noting that there is a tendency to play sharp and a tendency toward octave stretch. In addition, judging intonation and "doing" intonation have not shown significant relationships (Byo et al., 2011, p. 318) Burns

(1999, pp. 245–248) summarized the most important intonation adjustment trends: short-term variability, intersubject variability, and the tendency to compress smaller intervals and stretch larger intervals. It could be added that a certain harmonic context may tend to bias intonation closer to just intonation, as Leukel and Stoffer (2004) showed.

Classical singers, choir singers, vocal ensemble singers

There are presumably differences between intonation manners of solo singers and ensemble singers. Classical solo singers may concentrate on melodic procedures, whereas ensemble singers may focus on consonances of harmonic procedures and minimizing beats. Bohrer (2002) suggested that the opera singing style does not fit in ensemble singing. The singer's ability to control pitch by means of the aural feedback from acoustic context affects intonation remarkably. He assumes that the use of equal-tempered keyboards in singer training affects intonation and notes that there exists a different way of thinking: extending the number of pitches per octave. The categorical perception principle and the beat detection principle are the cornerstones for dealing with intonation in a performance context (Bohrer, 2002, pp. 32–36).

In the study by Hagerman and Sundberg (1980), two barbershop quartet singers performed a chord progression. Most intervals in the experiment deviated from the reference values of just intonation and Pythagorean tuning. In the dominant chord, the major third seemed to be a stretched version of a pure major third, but in the tonic chord, the major third was intonated as some kind of flattened version of the Pythagorean major third. The minor thirds were flatter than in just intonation (Hagerman & Sundberg, 1980, p. 42). Interestingly, the cent values of barbershop quartets singing chord progressions were very close to equal temperament. However, the authors did not mention this. In another study of barbershop singing by Sundberg (1982), barbershop singers seem to aim at pure (just intonation) intervals. The major third and the major sixth deviated the most compared to equal temperament, which refers to the harmonic component of this art form (Sundberg, 1982, pp. 60–64).

Price (2000) studied interval matching of undergraduate non-music majors. The participants were classified as uncertain, modulating, and certain singers on the basis of a singing test, where they sang a simple tune without accompaniment. Inaccurate singers were less in tune than modulating or certain singers. The acceptable reliability was an increment of 10 cents. Modulating singers echoed descending minor thirds as well as certain singers, but they could not maintain tonality. Poor singing skills cause problems for uncertain singers (Price, 2000, pp. 363–369).

Vurma and Ross (2006) investigated the intonation by singers. Individual singers varied as much as 50 to 55 cents in pitch during a production task (SD = 10 cents or less). Compared with equally tempered intervals, the minor second was performed narrower and the perfect fifth wider in both ascending and descending modes. The singers tuned the minor seconds and perfect fifths more accurately than tritones. Performed intervals were compared individually to the intervals of equal temperament on the basis of the fundamental frequency of 440 Hz. The investigators suggested that in their performance strategy, singers may have concentrated more on the individual interval sizes and less on the stability of the whole scale (Vurma & Ross, 2006, pp. 338–343). One might say that 55 cents out of tune sounds unsatisfying.

Pfordresher, Brown, Meier, Belyk, and Lioti (2010) introduced a distinction in the measurement of poor-pitch singing: the distinction between singing accuracy and singing precision. This measurement distinction is familiar within statistics but not yet in singing research. Accuracy in singing points to the average difference between the sung note and target pitch. Precision in singing refers to the consistency of sung pitches that are repeated independent of target pitch. According to this division, singing can be, for example, inaccurate but precise, accurate but imprecise, or inaccurate and imprecise. The results indicated that imprecise singing is widespread, whereas inaccuracy occurs at essentially lower rates. In addition, an inaccurate singer was also imprecise, but an imprecise singer could or could not be inaccurate. Thus, inaccurate singing reflects a more serious deficit than imprecision (Pfordresher et al., 2010, pp. 2182–2189).

Hedden and Baker (2010) investigated children's singing accuracy with piano accompaniment and a cappella using perceptual analysis and acoustic analysis, judging whether a perceived performance was in tune or out of tune. The authors speculate that singing without lyrics (with loo-syllable) would have weakened the results: Only 20% were singing in tune (a cappella and accompaniment, acoustic analysis). All in all, the authors recommend that accompaniment should be used only prudently (Hedden & Baker, 2010, pp. 42–44).

Devaney, Mandel, Ellis, and Fujinaga (2011) introduced an algorithm that automatically extracts performance data from the recordings of the singing voice. Participants were undergraduate and professional singers who sang Schubert's *Ave Maria* a cappella and with accompaniment. The interval widths for whole tones were measured to lie within the 196–209 cent range. In a cappella singing, undergraduate singers tuned both semitones and whole tones mainly narrower than professional singers. The undergraduate singers tuned their semitones (79–95 cents) close to the Pythagorean tuning (narrow semitones, high leading tones) and whole tones close to the equal temperament. Professional singers tuned semitones close to equal temperament and the whole tones close to just intonation. The descending intervals were, on average, 8 cents narrower than the ascending intervals (101 cents). The non-professionals' semitones tended to be smaller than the equal-tempered semitone. The professionals' semitones were closer to equal temperament. There was no significant difference between semitones sung a cappella and semitones sung with accompaniment (Devaney et al., 2011, pp. 115–121).

In Devaney's dissertation (2011), experiments with solo singers and vocal ensemble (SATB) showed no particular characteristic intonation tendencies that singers used in general. The overall tendency toward equal temperament was found despite a surprisingly wide range of intervals, both vertical and horizontal. Analyzing vertical intervals, the investigators found that in cadential contexts, vertical intonation was closer to just intonation than in non-cadential contexts (Devaney, 2011, pp. 253–254).

D'Amario, Howard, Daffern, and Pennill (2018) investigated a semi-professional a cappella vocal quintet in a longitudinal study using the homophonic arrangement of the chorale of J.S. Bach. The singers performed three repetitions of the piece before rehearsal and after rehearsal. In horizontal tuning, the participants intonated closer to equal temperament than just intonation, which happened throughout the measurements. In vertical tuning, major thirds were intonated a bit closer to just intonation than equal temperament, with the average size being 392.17 cents (SD = 27.56 cents). The results from pairs of singers deviated from each other. Minor thirds were intonated practically to equal temperament (the average size was 299.13 cents, SD = 29.28 cents). Tuning behavior in vertical thirds seemed consistent and repeatable. Investigators found four strategies for solving tuning strategies: Tuning "doubled" notes, balancing voices, tuning the whole chord, and tuning melodic intervals (D'Amario et al., 2018, pp. 6–14). Doubled notes seem to refer to the same pitch in different voices of an ensemble.

Computer-assisted methods for analyzing intonation in performance

Morrison and Fyk (2002) argued, "It seems clear that pitch alternatives advanced performers make do not conform to a specific tuning system" (p. 187). And further:

"It is probably inappropriate to say that performers play *in* a given system." These citations can issue a picture according to which intonation is accidental. It sometimes probably is.

Devaney and Ellis (2008) presented signal processing and machine learning methods for studying polyphonic vocal intonation practices that are not locked into a single reference system. Devaney and Ellis (2008, p. 142) refer to Backus (1969) and Barbour (1953): Vocal intonation is a combination of horizontal and vertical intonation and the weightings of these factors differ depending on musical contexts. According to Devaney and Ellis (2008), the new methodology constructs and expands the theory of tuning and intonation practices. Vertical intonation is based on sensory consonance, while horizontal intonation practices in performance can be related to musical expectations, musical meaning, and emotion. The purpose is to analyze the intonation of the recordings in terms of real musical performances. This technology helps investigators to estimate the perceived fundamental frequencies for the sung notes (Devaney & Ellis, 2008, pp. 142–152).

Vurma (2010) found that singers tended to sing melodic intervals according to equal temperament and preferred the preciseness of a melodic interval to the harmonic interval of accompaniment (Vurma, 2010, pp. 24–25). Fischinger and Hemming (2011) investigated individual intonation and timing measures of vocal ensembles. In their experiment, the fundamental pitch rose, on average, 25.12 cents from the beginning to the end. The fifths and octaves were intonated close to equal temperament. There was no tendency to pure intervals, but there was for sharp intonation. The SD of female singers was smaller than for male singers (Fischinger & Hemming, 2011, pp. 51–53).

Equal temperament turned out to be the reference system in the study by Devaney, Mandel, and Fujinaga (2012) among vocal ensembles. If the melodic intervals were not within one SD of equal temperament, the intervals were smaller, near the minor justly intonated minor whole tone (182 cents). Most of the vertical intervals fell within one SD of non-equal temperament tunings. Some exceptions were found. Ensemble 1 tuned the minor thirds (316 cents) and the major third (386 cents) in just intonation, and Ensemble 2 tuned the major thirds close to Pythagorean tuning (408 cents) (Devaney et al., 2012, pp. 515–516).

Howard, Daffern, and Brereton (2013) introduced a four-part chorale synthesis system that enables hearing the differences between just and equal-tempered versions of individual chords. The system also enables the tuning differences in items from the choir repertoire to be appreciated. One or more of its four parts can be replaced with a human singer whose fundamental frequency can be measured as they sing along with the other three parts. Fundamental frequency, vibrato rate and depth, overall amplitude, and vowels were controlled by the Xbox controller. The singers intonated sharply against a justly intonated version. Performances against an equal temperament reference were sung flat. It was assumed that tuning notes of chords to a maximum consonance involves the use of relative pitches. This can be a manner of intonation in a cappella singing and requires, naturally, critical listening skills. The application of a practical multi-part real-time synthesis system helps singers develop these skills (Howard et al., 2013, pp. 136–141).

Abeßer, Frieler, Cano, Pfleiderer, and Zaddach (2017) proposed a framework for analyzing tuning, intonation, pitch, modulation, and dynamics in monophonic solos of reed and brass instrument players on jazz recordings. The authors picked up high-quality transcriptions and separated the audio sample into a solo instrument and the rhythm section. The tuning frequency of the backing track was defined first. Next, the fundamental frequency and intensity contours were estimated for each note of the solo part. Among other features, intonation tendencies were derived from the collected data and analyzed together with data that were adopted from existing symbolic representations. Manual annotations and external metadata were related to analysis. The results showed a strong variation with different context parameters. A personal style seemed to be the most important factor, but there were also overall styles, and the specifics of the instrument played a role (Abeßer et al., 2017, pp. 173–176).

2.3.2 Intonation preferences and judgments

The present sub-chapter concerns intonation judgments and preferences: consonant–dissonant judgments, intonation and tone quality judgments, effects of reverberation, good–bad ratings, in-tune and out-of-tune judgments, and intonation adjustments.

Which tuning to prefer?

Loosen (1994) investigated the tuning preferences of highly trained violinists and pianists, as well as non-musicians, in an adjusting task where they were asked to set tone three (E, A, and B) computer-generated tones of eight-tone ascending and descending diatonic scales of C major. Violinists adjusted the tones closer to Pythagorean tuning than pianists (the average deviation from Pythagorean tuning was 3.5 cents). Pianists adjusted closest to equal temperament (*M* of constant errors was 0.6 cents). Non-musicians did not favor any specific intonation model. Loosen refers to his earlier findings and supposed violin intonation to be something between Pythagorean tuning and equal temperament (Loosen, 1994, pp. 223–224). As the research literature has shown, string players might tend to intonate sharp intervals, which means a close relationship to Pythagorean tuning. Therefore, it is understandable that they prefer to adjust near Pythagorean tuning. Piano players rehearse with equally tempered instruments—and adjust close to equal temperament. You prefer what you have gotten used to.

In the study by Nordmark and Ternström (1996), 16 musically experienced participants (choral conductors, choral singers, orchestral musicians) were asked to adjust the intonation of 20 major third intervals so that the result was pleasing with synthetic ensemble sounds. The major third of 395.4 cents was the preferred size, with an overall SD of 7.3 cents. The range of adjustment was from 388 to 407 cents. These results are closer to equal temperament major thirds than they correspond to major thirds of just intonation, and the major third of just intonation (386 cents) did not seem to be universally desirable (Nordmark & Ternström, 1996, pp. 59–61). It seems that purely intonated thirds are probably slightly strange to musicians. However, the simplest way to improve intonation in tonal homophonic texture is to "release" tensioned major thirds of major triads.

Long (2008) investigated perceived preference (most consonant) of harmony excerpts that were tuned to equal temperament, just intonation, and Pythagorean tuning. Equal temperament turned out to be preferred over other tuning alternatives in most passages. The choosing of one intonation system over another seemed not to occur accidentally. This is contradictory to her hypothesis, according to which beat elimination increases the perception of consonance regarding the musical sound. Further, beats (of small numbers) distort harmony consonance among similar frequencies (Long, 2008, pp. 99–103). This coincidence theory was originally based on early 17th century writers, including Benedetti, Galilei, Kepler, Mersenne, and Stevin (Cohen, 1984, pp. 11–12). It seems that the acceptance of equal temperament has increased.

Different judgments

In a study by Geringer and Madsen (1998), the participants were asked to rate excerpts on phrasing/expression, intonation, rhythm, dynamics, and tone quality to give an overall rating judging them as "good" or "bad." Musicians could very clearly discriminate between the good and bad performances. Most listeners (78%)

specified intonation in identifying the aspects most in need of improvement. The presence of accompaniment did not seem to affect tone quality and intonation ratings. The importance of good intonation and tone quality was secured to participants' perceptions and ratings. Other rating categories (phrasing/expression, rhythm, and dynamics) were less important (Geringer & Madsen, 1998, pp. 525–533). The importance of proper intonation is well seen in this paper.

Zabriskie (2011) studied the effect of reverberation time and dynamics on choral ensemble singers' preferences regarding tone quality and intonation in soloistic singing. The ratings for intonation showed that the listeners chose higher ratings to the forte reverberation stimuli over the forte non-reverberation stimuli. In addition, the piano reverberant ratings were higher than those of piano non-reverberant ratings. In tone quality ratings, the participants rated reverberant stimulus with forte dynamic level and piano dynamic level higher than the forte non-reverberant stimulus. In general, auditors were unable to distinguish perception of tone quality from intonation or intonation from tone quality. The reverberation added to performance masked intonation errors. The participants rated soloistic choral tone quality higher at the forte dynamic level, when the reverberation time was increased (Zabriskie, 2011, pp. 60–64). In the present research, the original design of the experiment of mistuning recognition was to use different sounds in samples to listen to. For practical reasons, there will finally be only one sound selected. A study by Zabriskie (2011) gives a hint that reverberation and dynamic variations influence intonation judgments.

In the experiment by Johnson-Laird et al. (2012), participants judged major, minor, diminished, and augmented triads on a scale of 1–7, highly pleasant (consonant) to highly unpleasant (dissonant). The measured roughness put those triads in a slightly different order. The lowest experienced roughness was experienced, again, with major triad and minor triad, in that order. The judgments did not follow the roughness values with diminished and augmented chords: the diminished triad had the highest experienced roughness value. In the second experiment, the authors studied the roughness of 43 four-note chords and ratings of a consonant–dissonant axis. The consistent major scale triads with thirds and with no thirds had the lowest rating. The inconsistent major scale chord and minor scale chord with thirds had practically the same rating, and the roughness values mainly followed the ratings. The third experiment showed that the presence of tonal syntax in chord progression can influence the pleasantness of heard chords. In particular, tonal chords were heard as more pleasant in a tonal sequence than in a random one (Johnson-Laird et al., 2012, pp. 26–30). The musical material was executed in equal temperament. One might speculate what different tuning alternatives would affect participants' judgments. A justly intonated major triad sounds different from the one in equal temperament. On the other hand, triads occurring in atonal texture might sound pleasant independent of a tuning system.

Larrouy-Maestri, Lévêque, Schön, Giovanni & Morsomme (2013) introduced a comparison of acoustic analyses and subjective judgments in evaluating vocal accuracy. Investigators found that subjective ratings by expert judges conformed to objective measures. The perceptual rating of the subjective analyses seemed more critical when an accurate singer sung a false note compared with an inaccurate singer. This study also underlines the importance of three criteria used in objective measurements: pitch deviation, the number of contour errors, and the number of tonality modulations (Larrouy-Maestri et al., 2013, pp. 3–4). This study is a good example of intonation judgments made with both subjective and objective methods.

As can be seen, a rather broad variety of results can be found regarding intonation preferences. Generally, just intonation, equal temperament, and Pythagorean tuning have been compared. On the grounds of previous research in the literature, there is a lack of experiments with innovative tuning alternatives and, for instance, old temperaments.

2.3.3 Pitch drift in performing situations

Pitch drift is, at least theoretically, a solution to the problem of the syntonic comma. If keeping vertical intonation pure, the consequence is pitch drift, and the horizontal intervals have to be altered by a syntonic comma. In previous studies, pitch drift has interested researchers in different ways. Using pitch drift in an auditory sample, however, is missing among these studies. Pitch drift was presented in Sub-chapter 2.1.7. There have been some investigations concerning this phenomenon within the last two decades.

Scholtz (1998, p. 10) says a "string quartet could not play passages containing a sequence of triads in just intonation without altering the melodic intervals and, possibly the overall level of pitch." Howard (2007b, p. 303) reminds us that the fall of the fundamental frequency can refer to pitch drift. Indeed, if a highly trained singing group gradually changes the fundamental frequency, it may not be a question about poor intonation but pitch drift. Sometimes both.

Kalin (2005) investigated the formant frequencies of a barbershop quartet, reminding that intonation in this kind of singing is of ultimate importance. As some kind of by-product, he found out that the fundamental frequency in vocal performances was falling in all recordings approximately 40 cents. He speculated that this could be the consequence of singing according to room acoustics (Kalin, 2005, p. 3, 40). Pitch drift was not mentioned in the study, but it might be possible that the fall of fundamental frequency can be caused by the factors of pitch drift: pure vertical intonation or aiming to pure vertical intonation. Or again, both.

Howard (2007a) studied intonation by an a cappella quartet (SATB) to clarify whether singers use equal temperament or non-equal temperament. The singers modified tuning in relation to each other toward just intonation. There were two tuning strategies with a cappella singers and choir conductors: to remain in pitch or to keep harmony consonant. The latter demands shifting the overall pitch in every modulation. It is possible that singers pursue consonant tuning and sacrifice the constant pitch. Interestingly, two of the quartets in the study claimed to have strived for a constant pitch level, but they actually tended to sing consonant chords with pitch drift. Singers in a cappella choirs tend to intonate in just intonation and the overall pitch drifts (Howard, 2007a, pp. 87–93). Further, Howard speculates:

> It is interesting to speculate on the skills that are required to tune intervals in equal temperament, since there is no readily available physical guide to be derived such as the absence of beating. This suggests that tuning notes in equal temperament must probably rely on memory fed by the ubiquity of equal temperament in the exposure of Western ears to music from an early age. (2007a, p. 93)

Howard continues: "*an a cappella group does indeed have to stray in pitch in order to stay in tune*. Choral conductors need to understand this and make appropriate pitching strategy decisions" (2007a, p. 94).

Howard (2007b) wrote four-part exercises with modulations for a cappella quartet (SATB) in sequential progression. As remembered, I analyzed the very example of Howard in Sub-chapter 2.1.7 (see Fig. 8). As Howard (2007b, p. 303) points out, it is not possible to both maintain just intonation in chord progressions and to stay in pitch throughout music that modulates in key. In that case, the pitch center will have to shift from its starting point; this is a discrepancy of just intonation. According to Howard (2007b, p. 303), singers prefer just intonation on average. Just intonated thirds and fifths seemed to be a proper approach, but the use of seventh in exercises caused difficulties in tuning accuracy. He claims that correcting the overall intonation pitch drift for its own sake in a cappella contexts with modulating harmony may be a mistake. If one demands the correction of pitch drift, one might need to modify the tuning all the time, like the American

Barbershop singers. Howard emphasizes that the meantone tempered organs give the opportunity for beat-free singing, especially if there are certain types of organs with alternative enharmonics available (Howard, 2007b, pp. 303–304, 314). To be more exact: Meantone systems are fixed, and they sacrifice fifths in normal 12 tones/octave keyboard. The problem of the syntonic comma does not disappear, but it transfers to fifths. This is, of course, one possible solution for the discrepancy of the syntonic comma, but it does not omit beats from narrowed fifths.

Hancock (2008) studied musicians' and non-musicians' aesthetic responses to pitch center changes. In stimulus excerpts, the pitch rose or fell one cent/second up to 300 cents rise/fall. There was also an excerpt that was stable in pitch. The participants were asked to react by recording their aesthetic responses via Continuous Response Digital Interface (CRDI). Hancock found a significant main influence for pitch condition and an interaction effect for musicianship status and pitch condition: Non-professionals' aesthetic responses were similar to the rise of pitch and stable pitch. The gradual change of pitch does not seem to bother most listeners (Hancock, 2008, pp. 85–94). Perhaps the audience could possibly be more prepared for pitch drift than professional musicians, who tend to relate pitch drift to poor intonation.

Devaney et al. (2012) introduced AMPACT, a MATLAB toolkit for automatically extracting, analyzing, and comparing performance data from the aligned recordings for which a score is available. The investigators studied four three-part singing ensembles with a short exercise by Benedetti. This Renaissance theorist designed the exercise to highlight the conflict of just intonation tuning and pitch drift. I made an analysis of this exercise in Sub-chapter 2.1.7 (see Fig. 5).

In the investigation of Devaney et al. (2012), the singers did not exhibit pitch drift. They did drift up slightly on average. Equal temperament turned out to be the reference system in this experiment. If the melodic intervals were not within one SD of equal temperament, the intervals were smaller, near the minor just intonation semitone (182 cents). Most vertical intervals fell within one SD of non-equal temperament tunings. Some exceptions were found. Ensemble 1 tuned the minor thirds (316 cents) and the major third (386 cents) in just intonation. Ensemble 2 tuned the major thirds close to Pythagorean tuning (408 cents) (Devaney et al., 2012, pp. 515–516).

Fischinger, Frieler, and Louhivuori (2015) studied the influence of room acoustics on tuning and drift, intonation of single pitches, and intonation on consonance. The investigators found a significant drift (−4.6 cents) in room size at a reverberation level of 1.77 s, which means a medium-sized "Concertgebouw"

(Fischinger et al., 2015, p. 12). Mauch, Frieler, and Dixon (2014) verified intonation drift. They investigated intonation and intonation drift in unaccompanied singing under three conditions (normal, masked, and imagined). The reference tuning system was equal temperament, and the song was familiar *Happy Birthday*. The results of recordings showed a median intonation drift with a value of 11 cents; 22% of observed drifts were significant while they were smaller than the median note error (19 cents). The clear majority of observed drifts were upward. According to the authors, drift is a true phenomenon and common in solo singing, and it is not correlated to musical background in addition to pitch or interval accuracy. Masking conditions did not affect singing intonation (Mauch et al., 2014, pp. 403–410).

In the study of D'Amario et al. (2018), there occurred no pitch drift among the participants of an a cappella singing quintet. This result did not corroborate with earlier findings of Howard (2007a, 2007b). The investigators supposed that the characteristics of musical material, individual singers, and the combination of singers affect the tuning of singing ensembles (D'Amario et al., 2018, p. 12).

Pitch drift is one way to understand the outline of just intonation discrepancies. Here lies the discrepancy of the syntonic comma. Although Howard does not explicitly mention the syntonic comma, his musical example involves a series of secondary dominants, each of which potentially causes the overall pitch to drift by a syntonic comma.

2.3.4 Synopsis of previous research on intonation preferences

As can be noticed from the grounds of previous sub-chapters, intonation in performance is not an unambiguous issue. An overview of measured intonation conventions helps one to understand the essence of intonation issues on the whole. A synopsis of previous research on this era is presented in Table 9.

Table 9. Synopsis of previous research on intonation preferences.

Theorem	More exactly	Reference
Sharp tendency is common.	Sharp tendency seems to be true among string instrument players.	Sundberg (1982); Kantorski (1986); Fyk (1998); Burns & Ward (1999); Bohrer (2002); Byo et al. (2011)
	Sharp tendency among wind players.	Duke (1985); Burns & Ward (1999); Morrison (2000); Kopiez (2003); Byo et al. (2011)

Theorem	More exactly	Reference
Mostly close to equal but occasionally just.	The intonation in performance among wind instrument players is a multilateral and complex phenomenon. Equal temperament has been found to be a common reference system among wind instrumentalists.	Duke (1985); Karrick (1998); Kopiez (2003); Leukel & Stoffer (2004)
	A flat tendency among wind players. Wind players tended to narrow ascending intervals and stretch descending intervals.	Duke (1985)
	Aiming at just intonation was seen. Flautists intonate near just intonation in thirds and sixths.	Karrick (1998); Leukel & Stoffer (2004)
	Musicians tended to sharpen higher notes and flatten lower notes.	Kantorski (1986); Bohrer (2002)
Singers' intonation depends on performing style.	Barbershop singing operates between just intonation and Pythagorean tuning.	Hagerman & Sundberg (1980); Sundberg (1982)
	Solo singers and ensemble singers use different strategies for intonation, and the latter mentioned aim to consonance and beat minimization. This seemed to succeed in vertical thirds.	Bohrer (2002)
	The vertical intonation was closer to just intonation in cadential than in non-cadential context, analyzing vertical intervals of vocal ensemble.	D'Amario et al. (2018)
	No particular characteristic intonation tendencies that singers used in general.	Devaney (2011)
	The performed intonation by classical singers can be remarkably inaccurate and imprecise.	Devaney et al. (2011); Price (2000); Pfordresher et al. (2010); Vurma & Ross (2006)
Horizontally equal, vertically just, sometimes sharp.	Equal temperament seemed to be a reference system, especially in horizontal intonation.	Devaney et al. (2012); Vurma (2010)

Theorem	More exactly	Reference
	In vertical tuning, just intonation thirds were used by one ensemble and Pythagorean thirds by another ensemble.	Devaney et al. (2012)
	Vocal ensembles had no tendency for just intonation, but rather for sharp intonation.	Fischinger & Hemming (2011)
	Choral singers sang out of tune with reference stimulus of just intonation.	Howard et al. (2013)
	Vocal polyphonic intonation is a combination of vertical and horizontal intonation.	Backus (1977); Barbour (1951/2004); Devaney & Ellis (2008); D'Amario et al. (2018)
Violinists preferred Pythagorean tuning; pianists preferred equal temperament.	Equal temperament turned out to be preferred over other tuning alternatives in most passages: The selection of one intonation system preferred over another seemed not to occur accidentally.	Long (2008)
	Pianists adjusted close to equal temperament. Violinists preferred Pythagorean tuning. Non-musicians did not favor any specific system.	Loosen (1994)
	Experienced musicians preferred major thirds (mean 395.4 cents) closer to equal temperament than just intonation.	Nordmark & Ternström (1996)
Good and bad performances were discriminated, but tone quality can be mixed with intonation.	Musicians could very clearly discriminate between good and bad performances. Most listeners (78%) specified intonation in identifying aspects of most in need of improvement. Tone quality was the next in order (17%). Choral ensemble singers were unable to distinguish the perception of tone quality from intonation or intonation from tone quality.	Geringer & Madsen (1998)

Theorem	More exactly	Reference
Reverberation masks intonation errors.	The room reverberation combined to make performance masked intonation errors.	Zabriskie (2011)
Major triad was experienced as the most consonant chord.	Major triad was the most consonant chord (rated 1.67), whereas minor triad had a rated dissonance of 2.41 on a scale of 1–7, highly pleasant (consonant) to highly unpleasant (dissonant).	Johnson-Laird et al. (2012)
Subjective judgments corresponded to acoustic analyzes.	In a comparison of acoustic analyses and subjective judgments in evaluating vocal accuracy, subjective ratings by expert judges conformed to objective measures.	Larrouy-Maestri et al. (2013)
Pitch drift can occur, and it does not necessarily bother.	A sequence of triads in just intonation without altering the melodic intervals can refer to pitch drift.	Scholtz (1998)
	Singers in a cappella choirs tend to intonate in just intonation and the overall pitch drifts.	Howard (2007a)
	It is not possible to both maintain just intonation in chord progressions and to stay in pitch throughout music that modulates in key.	Howard (2007b)
	Room acoustics had only a weak connection to intonation, but a drift (−4.6 cents) was found on a reverberation level of 1.77 s.	Mauch et al. (2014)
	Pitch drift is a true phenomenon and common in solo singing, and it is not correlated to musical background in addition to pitch or interval accuracy.	Fischinger et al. 2015
	The gradual change of pitch does not seem to bother most listeners.	Hancock (2008)
Pitch drift did not happen despite expectations.	The fixed fundamental frequency of pitch seems persistent: The singers did not exhibit the pitch drift.	Devaney et al. (2012); D’Amario et al. (2018)

Theorem	More exactly	Reference
Another aspect to pitch drift.	An equation to implement an additional pitch drift compensating mechanism by filling chromatic scale with 16:15 semitones (Octave = 1340 cents) or using both 16:15 semitones and greater chromatic semitones (135/128) which ends up to 1223.46 cents.	Stange et al. (2018)

Formatting Experiment 2

The second empirical experiment in this study will address the question of how receptive music professionals are for different usages of syntonic comma. As can be seen from previous studies presented, the general manner of approach to intonation experiments is to compare produced intonation to Pythagorean tuning, equal temperament or just intonation. However, as presented earlier, there have been a huge number of keyboard temperaments developed through the centuries. A majority of them could be used today—if the awareness of intonation issues was better. Therefore, Experiment 2 of this research charts out which ways of dealing with the syntonic comma in tonal and modal chord progressions are judged more preferable than other ways. Meantone tuning was a widely used keyboard temperament in the late Renaissance and early baroque periods. It is still in active use among early music specialists. However, the sensitivity for it has not been investigated, to my knowledge, in previous research. So, it was the apparent alternative for this experiment. There are lots of simple, tonal contemporary music works that could be played with meantone tuning, not to mention the early music repertoire. Surprisingly, perhaps, this usable tuning system has not inspired much empirical research. Therefore it was chosen for Experiment 2.

The hegemony of equal temperament in Western music culture and its intonation practices seems obvious. Likewise, in a few investigations of preferences for intonation systems, equal temperament seems to rule (see e.g., Kopiez, 2003, p. 404). Equal temperament obviously can provide targets for musicians' pitch matching. Hence, it was an obvious choice for this experiment because of its widespread hegemony of all Western music, independent of genres. As discussed in Sub-chapters 1.2 and 2.1.7, this hegemony of equal temperament might result in outstanding popularity in preferences of Experiment 2.

A new contribution presented in this experiment is that *local tempering* is a technical combination of just intonation and equal temperament. The second-degree minor triad (ii triad) with a syntonic comma is simply replaced with an equally tempered minor triad. The idea is to use pure triads where it is possible. Correspondingly, tempering is used only where it is necessary in the ii triad.

The second contribution is using pitch drift as an aural choice for intonation preferences. This phenomenon itself, as written earlier, has been known for centuries. Pitch drift was chosen on the basis of recent research literature. As written in Sub-chapter 2.3.1, it means a rise or fall of fundamental frequency during performance. Pitch drift is a consequence of vertically pure harmonic intonation in certain chord progressions and always in modulations. The investigations of pitch drift have concentrated on singing in performance and pitch drift: It seemed to be a true phenomenon according to these studies. It seems clear that pitch drift is related to pure vertical intonation, at least among well-trained solo or ensemble singers. However, it is too often straightforwardly associated with mistuned performance, although this may only reflect one possible aesthetic position. Hancock's (2008) observations of aesthetic responses to changes in pitch center were nearest to this experiment design. Pitch drift within an aural sample among other tuning alternatives has not presumably been examined earlier. Therefore, pitch drift will be one of the four tuning alternatives in the experiment of intonation preferences. The participants' reactions to chord progressions with pitch drift bring relevant information to develop intonation skills. At the same time, the whole phenomenon becomes more familiar in musical contexts.

2.4 Pedagogical motivations: Previous research

There will be numerous factors influencing intonation in performance: timbre is one of the most examined. Tools for improving intonation have also interested researchers, especially in music education. In the Sub-chapter 2.4.1, I will examine studies concerning factors influencing intonation, especially in the context of choirs and orchestras. In Sub-chapter 2.4.2, I will present investigations that consider tools that can improve intonation.

2.4.1 Factors influencing intonation

There are a number of aspects influencing intonation. Jeans (1937, p. 176) noticed that string players and singers may intonate differently with accompaniment in equal temperament and without accompaniment. Here, we find one aspect influencing intonation: accompaniment versus without accompaniment. I will introduce some investigations concerning factors influencing intonation.

Choirs

According to Ternström and Sundberg (1988), the topics of voice producing affecting intonation are breath support and vibrato in choir. The topic of room acoustics affecting intonation is the effect of SOR (singer spacing and room absorption on the self-to-other ratio). In their study, common partials, high partials, vibrato, and the interval significantly affected the accuracy of intonation among the choir singers. Reference vowels with common partials, which were strengthened by formants, were found to increase fundamental frequency precision. If the lowest common partial was strengthened, the accuracy of intonation increased. The most powerful effect was found when the first and the second formants reinforced the first and the second partials. The spectral properties of the reference sound affected the precision of a choir singer's fundamental frequency adjustment. Among the amateur bass singers, the deviation of fundamental frequency varied from 13 to 45 cents. In singing, there is a difference of 30 cents between the i-vowel and e-vowel in measured pitch (Ternström & Sundberg, 1988, p. 59–69).

To my experience, amateur bass singers with fundamental frequency errors of 45 cents cause damage to the intonation of choirs. A common worry among choirs is the lack of tenor singers. I think the more essential worry should be the intonation of bass singers.

Ternström and Karna (2011) note that intonation is one of the topics in choir acoustics. The topic of perception affecting intonation is pitch/amplitude effect. The pitch can differ a bit in the left and right ears. The topic of sound technology affecting intonation is the device for giving the starting pitch. The writers made a list about possible relevant factors in situations where a choir tends to go out of tune: the intrinsic pitch, the pitch-amplitude effect, breath support, and complex modulations (Ternström & Karna, 2011, pp. 280–282). Indeed, complex modulations can lead to out-of-tune situations: This phenomenon attaches to pitch drift.

Demorest and Clements (2007) studied the factors that influence the pitch matching of junior high school boys who were divided into three groups: certain, inconsistent, and uncertain singers. The inconsistent group performed better when there was a tonal context provided. Singing register does not necessarily influence pitch-matching or perception skills as long as tasks assessed are range appropriate. The margin of in tune and out-of-tune errors was 50 cents. To my touch, 50 cents sounds a lot. According to Demorest and Clements (2007, p. 200), choir teachers should concentrate more on dealing with the more basic issue of pitch matching. This skill seems to be built on several skills that may improve both the perception and production skills from contextual to isolated pitches (Demorest & Clements, 2007, pp. 199–200). The recommendations of just mentioned investigators seem foregone conclusion, but I have experienced same in practice.

Then, do the gestures help singers? To my experience, they do, as long as gestures are appropriate. Liao (2008) studied the effectiveness of gesture use in facilitating children's pitch accuracy. The study also compared the results between boys and girls. The gestures affected positively on children's singing accuracy when they sing tonal patterns. It is possible that the success in using gestures in singing is due to attitude toward motor learning. In addition, most participants had a positive attitude regarding gestures in singing. Both the girls and the boys sang more accurately with gestures than without gestures. The improvement of boys in singing accuracy with gestures was slightly greater than the improvement of girls. However, the girls sang more accurately than whether they used gestures or not (Liao, 2008, pp. 207–208). However, to my experience, the borderline where gestures may disturb singing is subtle. In particular, amateur conductors may gesture lavishly, which can even disturb singers.

Liao and Davidson (2016), too, clarified the effects of gesture as well as movement training on the intonation of children's singing. The context of this study was vocal warm-up sessions with regard to improving intonation. The participants (10–11 years old) were divided into three training groups. The participants who received gesture and/or movement training yielded significantly better improvement in singing in tune than those children who did not receive any training, which was also compatible with earlier findings. There were five different vocal patterns, and the ratings of the chidren's improvement varied between those patterns. Three gestures (gathering, pushing, and opening–closing) would seem to have positively influenced children's intonation (Liao & Davidson, 2016, p. 4, 14–15). These results abolish the doctrine of some choir conduction educators who emphasize that conductors should not express anything with the face.

Fischinger et al. (2015) studied how virtual, varied room acoustics (three levels of reverberation times) influenced choir singing with regard to intonation, loudness, tempo, and timing precision. The aspects of intonation investigated were tuning and drift, intonation of single pitches, and intonation on consonance. The findings showed that intonation is only weakly influenced by room acoustics. However, intonation analyses revealed an optimal singing room size on a reverberation level of 1.77 s (Fischinger et al., 2015, pp. 24–26).

Wind bands and orchestras

Garofalo (1996) listed 10 main factors that may cause poor intonation in band and orchestra performance: 1) condition and quality of the instruments and accessories, 2) basic playing procedures, 3) insufficient warm-up (wind instruments), 4) playing the standard tuning frequency (wind instruments), 5) psychological and musical phenomena, 6) pitch tendencies of instruments and performers, 6) poorly trained ears (students with little or no ear training), 8) poor balance (vertical dynamics), 9) poor seating arrangement, and 10) poor acoustics in the rehearsal and performance environments (Garofalo, 1996, pp. 9–15). Geringer and Worthy (1999, p. 147) approach this question more generally. According to them, pitch perception was influenced by several factors: fundamental frequency, tone quality, tuning situation, consistency across listeners, and additional factors. Jagow (2012, pp. 72–73) lists factors influencing pitch: Air, posture, embouchure, mouthpiece, amount of mouthpiece, angle of mouthpiece, lay of mouthpiece, barrel and bocal length, horn hand positions, tongue positions, reed condition, equipment, dynamics, pitch concept, balance, timpani pitch, percussion, and temperature are the factors affecting pitch. Several factors, indeed.

Powell (2010) summarizes that the effect of vocalization on wind instrumentalists' intonation skills is ambivalent and thus not clear. But temperature influences: The lowered external temperature lowers the pitch (Powell, 2010, pp. 183–184). I assume that every single wind player, at least wind conductor, has experienced that temperature really influences intonation. I remember dozens of performances with a wind ensemble in the circumstances of −15 °C in Finland. It is rather hopeless to stay in tune, especially if one is not familiar with intonation issues.

It is not indifferent which instrument is used as stimulus tone. Byo et al. (2011) write that it has become general that band and wind ensemble conductors use tuba as a reference for mass tuning: the players build primes and octaves on tuba sound. The authors doubted if players can resolve the second, fourth, and eighth partial, which means, of course, octaves built on a reference tone. In their findings, tuning responses to tuba stimulus deviated 9.05 cents on average. Among tuning responses, mean cent deviations were smallest to clarinet stimulus and largest to tuba stimulus.

Among flat tuning responses to oboe, the mean deviation was 7.92 cents; 40% of participants performed less accurately when they had to match their playing to tuba. Oboe and flute were not perceived as easiest to match tuning, but many players performed it most accurately (Byo et al., 2011, pp. 317–324). Perhaps orchestras should use clarinet as a reference tone player. This is, to my experience, rather common in Finland (because there are so few oboe players. However, let us forget tuba as reference tone.

Schlegel and Springler (2018) had recommendations to wind band educators. 1) Teachers should offer players sound models that are in tune and out-of-tune. 2) The use of chromatic tuners (3) Students should have the possibility to train pitch discrimination and pitch matching separately because these skills seem to be discrete abilities (Schlegel & Springler, 2018, pp. 403–404). These crystallizations seem reasonable.

Other factors influencing intonation

As written before, tone quality influences pitch perception. Worthy (2000) investigated the effects of changes in tone quality on the perception and performance of pitch among high school and university wind instrumentalists. The level of education and the tone quality of the stimuli and concert pitch and the tone quality of the stimuli were both interacted. In addition, a three-way interaction was found between the performance instrument, concert pitch, and the tone quality of the stimuli. “Bright” tones were judged sharper in pitch and “dark” tones flatter in pitch, which is line with earlier findings (see, e.g., Geringer and Worthy, 1999). The saxophone group performed clearly sharpest, with overall sharpness in subject responses. The clarinet group performed significantly sharper than the two brass groups. The wood wind groups performed sharper than brass groups in all of the tone quality conditions (Worthy, 2000, pp. 227–232).

Morrison and Fyk (2002, p. 190) noticed that specific feedback seems to improve pitch matching: The influence of feedback is better than the influence of instructions alone. Kopiez (2003) itemizes several factors influencing intonation: instrument imperfections, musical context, playing conditions, timbre, register, dynamics, player idiosyncrasies, beat frequencies, tone durations, size of intervals, effects of partial position of pitch production, and pitch classes independent from the context influence intonation (Kopiez, 2003, pp. 385, 408).

Van Besouw et al. (2008) itemize a long list of musical factors influencing intonation: The temperament/tuning system, the musical genre, the tonal hierarchy, the tonal function of individual notes, the melodic function of an individual note, its position in a melodic phrase, the context of performance and the rhythmical context (van Besouw et al., 2008, p. 154). This is something I have experienced frequently: When I improvise, I pay attention to music analysis factors like the following: “This is a leading tone,” “this is the third of subdominant chord,” “now I trifle with the blue tone,” etc.

Schlegel and Springler (2018) investigated the influence of tuner condition (displayed visually by tuners: flat = 437 Hz, in tune = 440 Hz, and sharp = 443 Hz) and instrumental experience on trombone players’ pitch-matching accuracy and other hand, tuning confidence. The players at college level intonated more accurately than high school trombonists in all tuner conditions. Experience linearly increased the accuracy of pitch performance. The performed cent deviations in sharp tuner conditions were larger than in-tune condition (440 Hz) and in flat condition (437 Hz): Players seemed to avoid flatness, and a slight sharp tendency was found (Schlegel & Springer, 2018, pp. 400–402). A sharp tendency is common, as noted in Sub-chapter 2.2.

Indeed, a huge number of factors seem to influence produced intonation. A music education professional, especially conductors, should recognize all these aspects. Intonation awareness is a vast potential for conductors and educators.

2.4.2 Improving intonation

It is comforting to know that intonation skills can be improved. A number of methods have been developed. In essence, it is a question of elimination of beats. The methods to achieve this are diverse. Let us create a short overview of a few of them.

Beat elimination

Frequently cited Miles (1972) studied beginning wind instrumentalists and their ability to improve their pitch-matching skills by learning to perceive beats in two or more mismatched tones. The participants practiced playing in unison and the following intervals: major third, perfect fifth, and triads with other instrumentalists. All the participants succeeded in a tuning unison free of beats at some time during each step of the study; 95% of the participants were able to tune a perfect fifth free of beats, and 88% of the participants were able to tune a major third free of beats. Furthermore, 80% of the participants were able to tune a perfect fifth free of beats in a triad, and 79% were able to tune a major third free of beats in a triad. The beat elimination process applied with the Intonation Trainer (an electronic pitch-matching device) was clearly effective in teaching beginning wind instrumentalists to play in tune (Miles, 1972, pp. 497–500). The results of this investigation are encouraging for educators. Garofalo (1996) reminds us that improving intonation in ensemble performance demands continuing listening for the presence of acoustic beats and sudden elimination of the pulsations by adjusting pitches with one's own instrument. The beat elimination process is one of the performance skills (Garofalo, 1996, p. 23).

Wolbers (2002) recommended singing in the band rehearsal because it can be a tool to explore pitch, balance, and musical syntax: Singing can also help to discover musical shapes and nuances. He also advises us to begin singing with melodic intervals and phrases. Players in the band should be encouraged to find the thirds by ear; the just intonation major third (386 cents) would be the aim. Singing helps the player to recognize intervals of the chords. Then conceptualizing and thus hearing the intervals before playing them with instruments improve intonation accuracy. Wolbers refers to Miles (1972) and describes the technique of matching the pitches and listening interference beats, which occur between the reference sound and the sound the player is producing (Wolbers, 2002, pp. 38–40). To my experience, major thirds are possible to achieve in wind ensembles, especially in brass ensembles, also without theoretical formatting. Even amateur players with modest technical skills can learn to avoid beats in simple exercises of building intervals and triads. This, however, requires professional conducting.

Likewise, Powell (2010, pp. 88–89) noticed that beat elimination and vocalization can improve the intonation of players. Ballard (2011, p. 30) accounts sensible to teach technique of pitch adjustment, where beat elimination rehearsal is essential. Kopiez (2003, p. 406) says, “Beat rates are only one acoustic cue in the successful adaptation to different tuning systems.”

Bohrer (2002) emphasizes that it is possible to detect a mistuning of the magnitude of syntonic comma through beat detection. Scooping and portamento could be present in any intonational strategy adopted by singers. Adequate training can help to overcome the predicament of vibrato's effects on intonation. The reference frequencies in flexible intonation may be changed during the performance (Bohrer, 2002, pp. 47–48). Bohrer helps us to approach the essential: syntonic comma mentioned.

Wuttke (2011) found that instruction plays an important role in producing desirable wind band intonation. A band director who concentrated on intonation (tuning octaves and chords and using the beat elimination method) of an ensemble achieved high scores in tests that measured equipment quality, knowledge of instrument pitch tendencies, and aural discrimination abilities. The next methods turned out to be effective in training intonation: voice groups tune perfect intervals, building chords (root-fifth-third), performing chords ascending and descending by semitone, performing exercises and stopping on chords (identifying the partials of the chord), and using beat elimination process to build the awareness of intonation (Wuttke, 2011, pp. 91–95).

I have noticed that conducting junior ensembles, particularly, demands conductor special skills dealing with intonation problems. The conductors of professional symphony orchestras may even ignore intonation issues, because the average level of intonation is “sufficient.” It really matters, a lot, who complies to conduct junior ensembles. Sometimes it is challenging to get one major triad to sound correctly. It is a most demanding work and calls for a deep understanding of intonation issues.

Algorithms for pitch matching

New technology has also brought new tools for intonation rehearsals. It is possible that technology makes everything easier, if we are unprejudiced. I will present a short overview of some of them.

Dalby (1992) developed and designed the Harmonic Intonation Training Program (HITP). The program had two parts: The first one included a lesson about basic acoustic foundations of two tuning systems, equal temperament and just intonation. The second part included drill-and-practice exercises using intervals, triads, and musical passages with two and three voices. The passages were chosen by using six criteria: conventional triadic harmony, homophonic texture, no unison doublings and cross-voicings, low complexity of rhythms, moderate tempos, and moderate registers for vocal writing. In Dalby’s study, 176 undergraduate music majors were tested by the Harmonic Intonation Discrimination Test (HIDT) as a pre-test. The use of the HIDT enhanced the post-test score. The attitudes of participants toward the training program were mostly positive (1992, pp. 141–151).

Milne, Sethares, and Plamandon (2007) introduced a system that simplifies intonation into a system that can be controlled and played easily. ”A higher-dimensional tuning system such as a just intonation can be mapped to a lower-dimensional tuning system by tempering its intervals” (Milne et al., 2007, p. 15). The syntonic rational continuum is a tuning apparatus, which is based on different sizes of perfect fifths (685–721 cents). The basement of this continuum is in Barbour’s thoughts (1951/2004), Lorenz (2001), Sethares (2004), and Huygens-Fokker Foundation Web site (see http://www.huygens-fokker.org). The isomorphic controller is a user keyboard interface for different tunings. The authors introduced keyboard fingering models to different tunings and keyboard fingering models for different tone order to several tuning systems, not only to equal temperament. There are also keyboard fingering models for different meantone temperaments. The authors introduced a cadence (I–IV–V–I) that can be played with identical fingering in all keys and in all tuning systems with a syntonic rational continuum (Milne et al., 2007, pp. 15–32).

Stange et al. (2018) have presented a dynamically adapting tuning scheme, which allows the musician to play in just intonation in any key. This novel tuning scheme solves a system of vertical intonation, horizontal intonation, and non-unique interval sizes. The authors presume that the art of instrument making will develop quickly, which probably means the decrease of instruments with fixed tuning. The significance of dynamically adapting constitutions of intonation will, on the contrary, increase (Stange et al., 2018, pp. 58–59).

All mentioned inventions aim at flexible intonation. However, the distance between the praxis of music education and technological inventions in intonation issues is quite long. Until now, to my experience, technology has advanced the usage of clinical equal temperament. A lot of opportunities could be put to use among new equipment.

Other methods for training intonation skills

Yarbrough et al. (1995) studied the effect of knowledge of directional mistunings on tuning accuracy of wind players. Total cent deviations from correct pitch and SDs grew smaller each year by years of instruction (Yarbrough et al., 1995, pp. 237–240). Garofalo (1996) noted several ideas for improving intonation: Treating intonation awareness of players, demonstrating “in-tuneness” and “out-of-tuneness,” requiring intonation charting with electronic tuner, teaching theory fundamentals and ear training, teaching singing, maintaining constant temperature and humidity, assigning parts for good balance, experimenting with seating (in orchestra), and refining warm-up and tuning procedures (Garofalo, 1996, pp. 84–85).

The following point is easy to understand: Playing one note alone does not improve a player’s intonation (Morrison, 2000, p. 47; Yarbrough et al., 1995, pp.

237–240). In my personal experience, some pedagogues use the method “play long notes” (alone). The benefit of these exercises seems minor from the intonation’s point of view.

Morrison (2000) investigated band students and the effect of melodic context, tuning behaviors, and experience on intonation accuracy. Intonation accuracy was noticed to improve with experience: The deviation from optimal pitches played by instruments got smaller every year (from 25.06 cents to 8.23 cents, SD) in seven years. Melodic context did not seem to affect performance accuracy. The absence of a melodic context seemed to have a significant impact on performance accuracy. Participants responded to tuning pitch more accurately than for melodic pitches. Tuning behaviors (tuning one’s own instrument to a single pitch, verbal instruction to play in tune, and receiving no information) did not seem to influence intonation accuracy (Morrison, 2000, pp. 47–49). Totally useless, in my opinion, are the exclamations like “listen to the intonation,” “listen to the each other,” and “this is out of tune.” Perhaps to most common fallacy is to judge all mistunings to be “flat.” Conductors should know (and hear) what to correct.

Pasqua (2001) developed a method to develop intonation awareness and improve tuning skills of high school wind instrumentalists. This method was used during regularly scheduled instrumental lessons, and it was designed in a cooperative learning model using four phases of tuning activities. The method was evaluated in terms of student skills, attitudes, and feasibility of implementation: Thet adjusted flat and sharp pitches, pure fourths, and pure fifths. The results showed that the time of tuning shortened remarkably, tuning accuracy was improved, and the confidence in participants’ tuning abilities was improved. In addition, the participants seemed to enjoy the cooperative learning approach, and they were able to implement intonation awareness studies during scheduled lessons (Pasqua, 2001, pp. 92–95). Pasqua (2001, p. 96) writes: “Students were able to explore, express, and evaluate ideas as they improved their intonation awareness and tuning capabilities.” This citation is encouraging.

Schellenberg and Moreno (2010) studied the connection between musical training, pitch-processing speed, frequency discrimination, and general intelligence (*g*). Musically trained and untrained participants achieved similar results on a measure of g. Musical training was observed to have a positive influence on pitch-processing speed and relative pitch and frequency discrimination (Schellenberg & Moreno 2010, pp. 214–216).

Villegas and Cohen (2010) developed computer sofware that made it possible to use adjustable intonation. The program adjusted the maximum pureness to intervals. The aim of using this program was to minimize the roughness of sonorities that are parallel, and which can be measured. This would be done as the sonorities are produced by calculating the pitch of each tone, which happens in real time (Villegas & Cohen, 2010, pp. 75, 90).

As can be seen, most of these approaches ignore the structural mistuning that the syntonic comma represents. Bohrer (2002) and Kopiez (2003) are exceptions. It would probably be easier to concentrate on minimization of beats if one recognizes the places where tempering is necessary (if pitch drift is not desirable).

2.5 Research questions

The first large issue of the two experiments of this research, as justified in previous sub-chapters, is the phenomenon called the syntonic comma. It will be investigated through two approaches: the first of these concerns the recognition of the syntonic comma. To the best of my knowledge, aural recognition of the syntonic comma has not been investigated in empirical research. This research aims to bring the phenomenon of the syntonic comma audible and visible with Experiment 1 (see Chapter 3). The second approach is the usage of the syntonic comma, which is presented and underlined with Experiment 2 in Chapter 4.

For this research, the intonation scale was extended to allow certain tonal and modal triadic progressions. As explained in Sub-chapter 2.1.5, just intonation scale leaves the second-degree minor triad mistuned by a syntonic comma concerning both the third and the fifth of the root. Hence, the “mistuning” in this experiment is the second-degree minor triad (ii triad). One starting point for the study was the simple idea that these mistunings would be easiest to recognize in simple harmonic contexts.

Experiment 1 (recognition of mistuning) will chart out the recognition of the syntonic comma in the context of chord progressions involving target chords mistuned by a comma. Two research questions will be addressed:

1. To what extent do young music learners recognize mistuned triads in simple four-voiced just intonation harmony?
2. To what extent can the recognition of the mistuned triads be explained by musical features, such as the complexity of harmony or the target location, and the participants’ individual features (e.g., instrumental experience)?

The location of the target here simply means the location of the mistuned triad in chord progression listened to in Experiment 1. Assuming that young music learners cannot recognize the mistunings in Experiment 1, the relevance of the syntonic comma to music education could be called into question. However, if they do significantly recognize these mistunings, it would become a relevant question how to deal with the comma—how to *use* it. What I mean by usage is that the problem of syntonic comma could be solved in several different ways. First, as explained above, the comma could be distributed to the whole tuning system, in which case we often speak of temperaments. Second, we could locally “correct” the mistuning in the vertical chords where it occurs. Third, it would also be possible to transfer the comma to melodic movements, causing pitch drift to happen. Syntonic comma actually cannot be eliminated—we must only deal with it in one way or another.

Experiment 2 (intonation preferences) will explore the following three different ways of using the syntonic comma. First, I have chosen to use two varieties of distributing the comma—meantone tuning and equal temperament. Second, local tempering will substitute the equal-tempered ii triad (in major keys) for the mistuned one in a (modified) just intonation scale. The fourth usage of the syntonic comma is pitch drift. Here, two further research questions will be addressed:

3. Which usages of the syntonic comma university music students and professional music educators prefer in tonal and modal four-part texture?
4. To what extent can these preferences be explained by the participants’ individual features (e.g., choral experience)?

The third objective of this dissertation is to pave the way for how the recognition and usage of the syntonic comma, as assembled in Experiments 1 and 2, could help in teaching intonation skills in music education. The results of Experiment 1 and 2 are hoped to bring practical implications that can be deduced based on two empirical experiments of this research and, on the other hand, based on research literature concerning intonation issues from the music education point of view. Music educators may benefit from increasing awareness of intonation issues. Which factors influence pitch matching? How can intonation be improved in practical situations of music?

After the two empirical experiments of this work, I will also be able to address the potential pedagogical implications of the results. In this context, previous research literature regarding intonation issues in musical performance may also be interpreted from a pedagogical point of view. As a whole, the dissertation thus aims to strengthen the pedagogy of intonation issues in music education.

The answers to the research questions are planned to be received by means of two music psychological experiments. The original musical material was developed first for the experiment on recognition of mistuning (Experiment 1). There were 40 chord progressions that were developed based on certain music analysis premises. After this material was made, 30 of 40 chord progressions were selected for the following experiment on intonation preferences. The complete description of Experiment 1 (recognition of mistuning) is presented in Sub-chapter 3.2 and Experiment 2 (intonation preferences) in Sub-chapter 4.2. Both experiments of this research are hoped to provide new tools for music education and instrumental pedagogy concerning the problem of how to deal with the problem of the syntonic comma.

2.6 Research process

I contacted three school units in December 2014. The participants in Experiment 1 were 166 pupils in music-intensive classes in two comprehensive schools, primary education (from grades three through nine age 9–16 years), in one secondary school (17–19 years) and university students (music education with a background in music-intensive classes) in Finland. The experiment was planned so that the session could be carried out during the school lesson. The experiment sessions were carried out in school rooms with equal written and aural instructions and with equal technical circumstances. The auditory instructions implemented in Experiment 1, the questionnaire, and the response packet are presented as written in Appendix 1. The approval form for parents of the underaged participants of Experiment 1 is presented in Appendix 2. The data was collected with a questionnaire on the front page of the response packet during spring 2015, and it was entered into the SPSS software in June 2015.

The analyses of the collected data, in the first place, were implemented through the SPSS software (version 24, with TETRA-COM SPSS syntax program; see Lorenzo-Seva & Ferrando, 2012) for estimating the tetrachoric correlations to be used in exploratory factor analysis (hereafter EFA) and principal component analysis (hereafter PCA).

The character of this research is purely quantitative, and it required statistical processing. A reasonable number of figures and tables were produced to illustrate the analyses of the results. In addition to statistical methods, a number of music theory analyses were used in analyzing the results of the experiments. Naturally, music theory issues were present in the phase on composing the chord progressions.

The interpretations, conclusions, and deductions of the statistical analyses attached to Experiment 1 are presented in Sub-chapter 3.3.

In Experiment 2 (intonation preferences), the participants ($N = 93$) were university music students and professional music teachers from two Finnish universities with the age of 18 years or older. The participants were asked to fulfill the approval form (see Appendix 3). They received aural instructions and wrote their answers on a response packet (see Appendix 4). The experiment sessions were carried out in rooms of a university environment and once in a private apartment with equal written and aural instructions and with equal technical circumstances. The data were collected between May 2015 and October 2016 and were entered into SPSS software in June 2015 and October 2016.

The analyses of the collected data, in the first place, were implemented through SPSS software. The quantitative results were subjected to interpretative analyses in terms of music theory. The interpretations, conclusions, and deductions of the statistical analyses attached to Experiment 2 are presented in Sub-chapter 4.3.

Reliability and validity are estimated separately when reporting both experiments. The discussion regarding both experiments is introduced in Chapter 5.

3 Experiment 1: Recognition of mistuning

Now, it is time to come back to the roots, the pitch discrimination of intervals and chords. The following main chapter will present an experiment in which the recognition of mistuned triads was performed by young music hobbyists. The first Sub-chapter 3.1 repeats shorty the aims of forthcoming experiment, recognition of mistuning. Method of this experiment is described in Sub-chapter 3.2. The results of experiment are presented in Sub-chapter 3.3. Reliability and validity are included in Sub-chapter 3.4.

3.1 Aims of Experiment 1

As remembered from Sub-chapter 2.1.5, the by-product of just intonation is the second-degree minor triad, which is mistuned by a syntonic comma. The main purpose of Experiment 1 was to find out how well the participants recognize this mistuned target triad in certain chord progressions, while other triads of chord progressions are purely tuned in just intonation. In particular, it was hoped that the experiment would shed light on participants' ability to perceive a mistuned triad in tonal environments representing varying levels of harmonic complexity. In addition, there was a certain interest in exploring how the false judgments in participants' answers were divided between purely tuned minor and major triads. There were only pure minor and major triads to misattribute.

3.2 Method of Experiment 1

This sub-chapter is divided on five sub-chapters. Sub-chapter 3.2.1 includes the essential information of the participants of Experiment 1. Musical material is described in Sub-chapter 3.2.2 and it is quite a wide overview of self-made chord progressions used in this experiment. Sub-chapter 3.2.3 introduces the design of this experiment. Procedure is presented in Sub-chapter 3.2.4 and data analysis in Sub-chapter 3.2.5.

3.2.1 Participants

The participants were 166 pupils in music-intensive classes in comprehensive school, primary education (third, fourth fifth, sixth, seventh, eighth, and ninth grades), secondary school, and university students (music education). All participants lived, in the Finnish context, in a rather big town (approximately 200,000 inhabitants). There were 54 male participants and 112 female participants. The youngest participants were 9 years old, and the oldest participant was 35 years old. The distribution of participants according to school level:

- 80 pupils at comprehensive school, primary education, music class (third, fourth, fifth, and sixth grades)
- 64 pupils at comprehensive school, music class, upper grades (seventh, eighth, and ninth grades)
- 12 students at secondary school (for ages 16–19) with an extended music program
- 10 university music students with background in music class.

All participants were asked to announce in which instrument group their main instrument belonged to, and 53 of the participants (31.9%) identified their main instrument to be in the group of string instruments. Also, 53 participants belonged to the group of piano, kantele, guitar, harp, or percussion, while 42 (25.3%) played a woodwind instrument, and 17 (10.2%) played a brass instrument.

Further, all participants were divided into three groups based on the voice they use to sing in the choir: top voice (59 participants, 35.5%), middle voice (64 participants, 38.6%), or bass voice (41 participants, 24.7%). The participants had played their instruments on average 6.1 years (*M*=6.14, SD = 3.9). The shortest time was one year, and the longest time was 22 years.

3.2.2 Musical materials

There were 40 chord progressions to be listened to. Every chord progression included seven triads. The first two triads were half notes in duration, while the third, fourth, fifth, and sixth triads were quarter notes, and the final triad was whole notes. Fig. 10 shows an example of chord progressions in Experiment 1.

Fig. 10. A sheet music example of a chord progression of Experiment 1, the target triad circled.

The stimulus materials for the experiments were chord progressions in which the second-degree minor triad (mistuned by a syntonic comma) was presented in three levels of complexity. The chord progressions were composed through extensive music analysis work (presented as follows) and prepared for presentation first by Finale notation software. The MIDI files of Finale files were converted to Logic Pro software. The tuning system used in this experiment was assembled into Logic Pro software. Audio samples were converted to WAV files and were burnt to the CD record. The complete material is presented in Appendix 5 and 6.

Each of the chord progressions included the target triad vertically mistuned by a syntonic comma. They were performed in a "chorale tempo" of 52 bpm and with a commonly used electrical sound: the Korg M1 piano sound.

The samples consisted of 40 triadic progressions. All possible triadic progressions of triadic harmony were introduced in a fixed just intonation temperament. This exact scale can be called the modified just intonation scale. It was developed for this purpose, but history knows the same scale by different names. In the *Continuum Encyclopedia of Popular Music of the World, Part 1 (Performance and Production, Volume 2)*, it is simply called the "just intonation scale" (Horn, Laing, Oliver & Wicke, 2003, pp. 596–600).

The location of the mistuned target as explained earlier, varied between four locations in the stimulus chord progressions. The participants were asked to listen to the third triad (Location 1/4), the fourth triad (Location 2/4), the fifth triad (Location 3/4), and the sixth triad (Location 4/4). There were 10 chord progressions with the syntonic comma in each of the four locations.

The tuning system used in the chord progressions of Experiment 1 was constructed out of three third related piles of three pure fifths, as seen in the lattice in Fig. 11. It is one of the possible 12-tone just intonation scales.

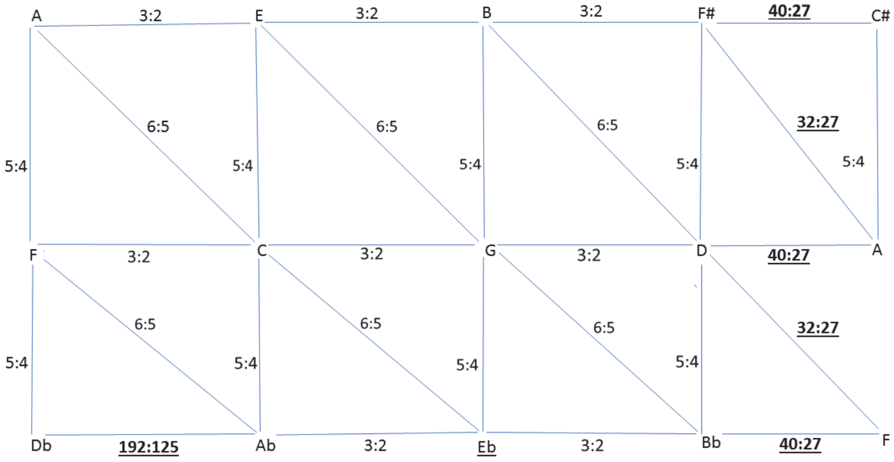

Fig. 11. The just intonation scale presented as a lattice.

The same scale in C is introduced in Table 10.

Table 10. Just intonation scale.

Scale attributes	Semitone	Minor third	Augmented fourth	Minor sixth	Minor seventh	Diatonic intervals of just intonation scale to the right	Major second	Major third	Perfect fourth	Perfect fifth	Major sixth	Major seventh
Cents	70.67	315.64	590.22	813.69	1017.60	O	203.91	386.31	498.04	701.96	884.36	1088.27
Ratio	25/24	6/5	45/32	8/5	9/5	1/1	9:8	5/4	4/3	3/2	5/3	15/8
Solfeggio	C#	Eb	F#	Ab	Bb	C	D	E	F	G	A	B

There were 12 pure intervals of diatonic triads. Diminished fifth of 64:45 is not used in becoming chord progressions. All those intervals are presented in Table 11.

Table 11. Pure intervals of diatonic triads of the just intonation scale in C.

Interval	Ratio	Cents
C-G	3:2	(701.96 cents)
C-E	5:4	(386.31 cents)
E-B	3:2	(701.96 cents)
E-G	6:5	(315.64 cents)
F-C1	3:2	(701.96 cents)
F-A	5:4	(386.31 cents)
G-D1	3:2	(701.96 cents)
G-B	5:4	(386.31 cents)
A-E1	3:2	(701.96 cents)
A-C1	6:5	(315.64 cents)
B-F1	64:45	(609.78 cents)
B-D1	6:5	(315.64 cents)

The scale made it possible to use two kinds of altered triads in just intonation: Modally altered major triads (III and VI) and the chromatically altered V/II. The just intervals of altered triads in C are presented in Table 12.

Table 12. Pure intervals of modally and chromatically altered triads of the just intonation scale in C.

Interval	Ratio	Cents
Ab-Eb1	3:2	(701.96 cents)
Ab-C1	5:4	(386.31 cents)
Eb-Bb	3:2	(701.96 cents)
Eb-G	5:4	(386.31 cents)
A-E1	3:2	(701.96 cents)
A-C#1	5:4	(386.31 cents)

This scale includes six pure major triads and six pure minor triads, which are presented in Table 13.

Table 13. Pure major and minor triads of the just intonation scale.

Pure major triads	Pure minor triads
C-E-G	C-Eb-G
Eb-G-Bb	E-G-B
F-A-C1	F-Ab-C1
G-B-D1	G-Bb-D
Ab-C-Eb	A-C1-E
A-C#1-E1	B-D1-F#1

All these just intonation triads included a downside, as remembered from previous chapters: The second-degree minor triad is mistuned by a syntonic comma. **F#-A** is the same interval as re-fa, Pythagorean minor third, 32:27 = 294.13 cents. **F#-C#1** is the same as **D-A** (40:27 = 680.45 cents). This is called, as mentioned earlier, "Wolf fifth." However, this chord degree (**F#-A-C#**) was not used in chord progressions. **D-F#** works very well (5:4 = 386.31 cents), but **D-A** is not usable, as mentioned.

C#-E is a pure minor third, but **C#-Ab** (743 cents) is not acceptable as a perfect fifth. **C#-F** is also unusable (32/25 = 427.37 cents). **C#-F-Ab** is extremely stretched. **F#-Bb** is also maximally stretched (32/25 = 427.37 cents) and the fifth, **F#-C#1** (40:27 = 680.45 cents) is narrow by a syntonic comma, as mentioned. **E-Bb** is 3:2, but **Eb-F#** is too narrow, 75/64 = 274.58 cents. **E-B** is 3:2, but **E-Ab** is too sharp, (32/25 = 427.37 cents). **Ab-Eb1** is pure fifth (3:2), but the minor third **Ab-B** is too narrow, (75/64 = 274.58 cents). **Bb-D1** is 5:4, but **Bb-F1** is too narrow, 40:27 = 680.45 cents. **Bb-C#** is absolutely too narrow, 125/108 = 253.08 cents. The minor chord **Bb-C#1-F1** has the most unsatisfying tuning in this temperament and is thus completely unusable. **B-Eb1-F"1** cannot be used because of the very sharp major third **B-Eb1** (32/25 = 427.37 cents). **B-D1-F#1** is a pure minor triad, as noted. The tuning of **F#** is insignificant in this experiment because it was not used in these chord progressions.

There are two kinds of major seconds (203.91, 182.40 cents) and even four kinds of minor seconds (70.67, 92.18, 111.73, and 133.24 cents). The syntonic comma appears here, too: The difference between the minor second of 25:24 (70.67 cents) and 135:128 (92.18 cents) is the syntonic comma of 21.51 cents (81:80) as well as the difference between the minor second of 16:15 (111.73 cents) and 27:25 (133.24 cents). Further, the difference of the major second of 9:8 (203.91 cents) and 10:9 (182.40 cents) is the syntonic comma, too.

As mentioned earlier, the experiment consisted of chord progressions, which are divided into three categories according to complexity. These samples were performed through the maximal pure scale. All categories contain triads from all scale degrees except for the seventh degree. Categories are presented as follows.

Chord progressions, Category 1

Most chord progressions in Category 1 are not typical tonal cadences. The purpose was to create tonally neutral chord progressions. Possible tonal expectations might have an influence on the recognition of mistuning by means of recognizing the chord degree. Syntonic commas are located vertically in the second-degree minor triad (ii triads, marked as an *italicized* font). There were 16 chord progressions, each of which included seven triads. Some chord progressions do not stay in the major key they started. Some chord progressions do not stay in the minor key they started. Some chord progressions stay "unfinished," at iii, IV, V, or vi triad. The purpose is to recognize the mistuning, not the tonal function, as subdominant. Seventh chords were omitted from the final score. This issue is discussed in Subchapter 5.7.

The main idea of chord progressions of Category 1 is that the mistuned triad appears only between I and iii triads. These triads appear in root position and both inversions. Also, the mistuned triad by a syntonic comma in the third interval and in the fifth interval appears in all inversions. In the stimulus set for Category 1, the comma triad appeared four times in each of four consecutive positions of the chord progressions, from the third to sixth chord of the test trial. For simplicity, these four positions will be referred to as triads 1–4 (triads 3, 4, 5, and 6). For each position, the triads before and after the target appeared once in all four possible combinations of first and third degrees. In Category 1, the triads before and after the target (the second-degree triad) are the following: iii – *ii* – I, I – *ii* – iii. I – *ii* – I, and iii – *ii* – iii. There were no syntonic commas in melodic lines in any voice. These chord progressions are presented in Table 14.

Table 14. Chord progressions, Category 1.

Chord progression number	Half note	Half note	1st triad	2nd triad	3rd triad	4th triad	Whole note
			Quarter note	Quarter note	Quarter note	Quarter note	
1.	I	IV64	I	vi	iii	*ii*	I
2.	I	vi	iii	V	I	*ii6*	iii
3.	I	iii	vi	IV	I64	*ii64*	I
4.	I	V6	I	vi	iii	*ii*	iii
5.	I	IV	vi	iii	*ii*	I	V
6.	I	vi	IV	I	*ii6*	iii	vi
7.	I	I6	IV	I64	*ii64*	I64	V
8.	I	V6	I	iii	*ii6*	iii6	vi
9.	I	vi	iii6	*ii64*	I	I6	V
10.	I	V6	I	*ii6*	iii	V	I
11.	I	IV	I6	*ii6*	I64	V	I
12.	I	vi6	iii64	*ii64*	iii6	vi	IV
13.	vi	iii	*ii*	I	IV	vi	iii
14.	vi	I	*ii6*	iii	vi	I64	V
15.	V6	I	*ii*	I	IV	I	V
16.	I	iii64	*ii64*	iii6	vi	I64	V

In Fig.12 we can see a sheet music example of chord progression from Category 1.

Fig. 12. A sheet music example of a chord progression from Category 1.

Chord progressions, Category 2

The main idea of chord progressions of Category 2 is that the comma triad appears between triads on the first and third, fourth, and sixth degrees with various combinations. Either IV triad or vi triad are surrounding the target (*ii*) triad. These surroundings are presented in Table 15.

Table 15. Triads surrounding the mistuned triads in Category 2.

Preceding triad	Mistuned triad	Following triad
I	*ii*	vi
iii	*ii*	IV
IV	*ii*	vi
vi	*ii*	IV
vi	*ii*	vi
IV	*ii*	IV
IV	*ii*	iii
vi	*ii*	I

Triads on the third degree appear in root position. I triads appear in root position and first inversion. IV triads appear in root position and second inversion and vi triads appear as all forms of triads.

The triad of the second degree with a syntonic comma in the third interval and in the fifth interval appears in the root position and both inversions. The placement of the mistuned triad changes three times: The comma triad is the third triad, the fourth triad, the fifth triad and the sixth triad, four times of each. In addition, there are 10 triads that include the syntonic comma in the melodic movement. In the eighth and ninth chord progressions, there are two melodic movements with melodic movements. The complexity of harmonic changes increases in a controlled manner in Category 2. These chord progressions are not typical tonal cadences, either. Syntonic commas are located vertically in ii triad (*ii* marked as *italicized* font). There are also 12 syntonic commas (horizontally) in melodic lines, marked with black arrows in Table 16:

- CAT2/1. Melodic syntonic comma in middle voice
- CAT2/2. Melodic syntonic comma in middle voice
- CAT2/4. Melodic syntonic comma in middle voice
- CAT2/5. Melodic syntonic comma in top voice
- CAT2/6. Melodic syntonic comma in top voice
- CAT2/8. Melodic syntonic comma in bass voice and in middle voice
- CAT2/9. Melodic syntonic comma in top voice (G/B-F/C) and in bass voice (Dm-Am)
- CAT2/12. Melodic syntonic comma in middle voice
- CAT2/14. Melodic syntonic comma in middle voice
- CAT2/16. Melodic syntonic comma in bass voice

Table 16. Chord progressions, Category 2.

Chord progression number	Half note	Half note	1st triad	2nd triad	3rd triad	4th triad	Whole note
			Quarter note	Quarter note	Quarter note	Quarter note	
1.	I	I6	*ii6*	vi	V →	IV	I
2.	I	iii	*ii64*	IV →	V	vi	iii
3.	I	I6	*ii6*	vi	V	vi	iii
4.	vi	iii	*ii6*	IV	V →	IV	I
5.	I	I6	IV →	*ii6*	vi64	V	I
6.	I	iii	vi	*ii64*	IV →	V	iii
7.	I	iii64	vi	*ii6*	vi64	V64	I
8.	IV	I6	IV →	*ii*	IV →	V	iii
9.	IV	I	V6 →	IV64	*ii* →	vi	iii
10.	vi	I	V6	vi	*ii64*	IV	I
11.	I	iii	V64	vi6	*ii*	vi64	I
12.	V	I	V6 →	IV64	*ii64*	IV	I
13.	I	iii	vi64	V64	IV64	*ii*	iii
14.	vi	I64	IV6 →	V6	vi6	*ii*	I
15.	I	iii64	vi	V6	vi6	*ii64*	I
16.	I	I6	IV →	V64	IV64	*ii*	iii

Fig. 13 illustrates an example of chord progression with melodic commas.

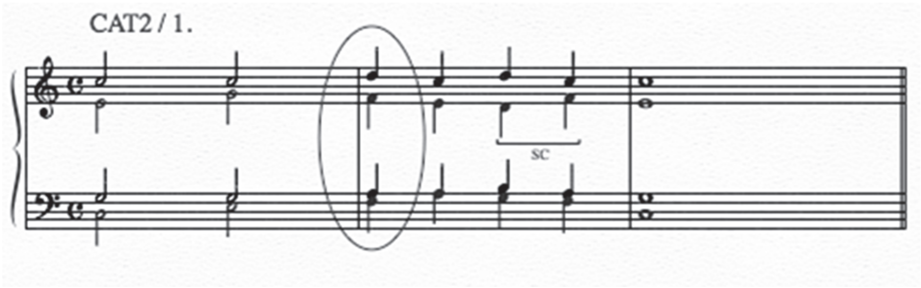

Fig. 13. A sheet music example of a chord progression with melodic commas from Category 2.

Fig. 14 illustrates an example of chord progression without melodic commas.

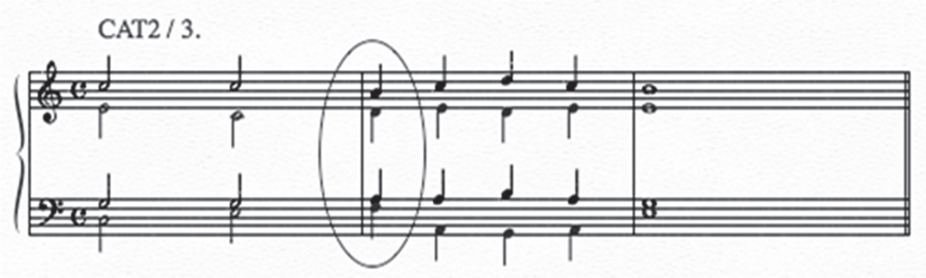

Fig. 14. A sheet music example of a chord progression with no melodic commas from Category 2.

Chord progressions, Category 3

In Category 3, in every chord progression, there is either the major triad at the third degree or at the sixth degree. The main idea of chord progressions of Category 3 is modally altered triads (Eb-major triad, Ab-major triad in C), which are vertically pure major triads. They never precede the comma triad or appear as the following triad of the comma triad. In addition, there is a modally altered triad in the 5th degree (Gm) in one chord progression. If the participants really listened to impurities of triads, they should not be disturbed by pure modal triads.

The construction of two nearest triads of the target triad is almost identical with Category 1: A triad right before the mistuned triad and the following triad after the target triad is either the I triad or the iii triad.

These triads appear in root position, as first inversion and as second inversion. The mistuned targer triad also appears in root position, first inversion, and second inversion. The location of the target triad changes three times: It is the third triad, the fourth triad, the fifth triad and the sixth triad, two times of each.

The chord progressions in Category 3 are not typical tonal cadences, either. Syntonic commas are located vertically in the comma triad, marked by an *italicized* font. There are no syntonic commas in melodic lines in any voice. The melodic movements to modally altered triads include a semitone (25:24 = 70.67 cents) between the major third of and the flattened third and between the sixth and lowered sixth of the root. The chord progressions of Category 3 are presented in Table 17.

Table 17. Chord progressions, Category 3.

Chord progression number	Half note	Half note	1st triad	2nd triad	3rd triad	4th triad	Whole note
			Quarter note	Quarter note	Quarter note	Quarter note	
1.	I	iii	*ii*	iii	IV	VI	I
2.	I	iii64	*ii64*	I64	III	v	I
3.	I	V6	I	*ii*	iii	III6	I
4.	vi	IV	I6	*ii6*	I64	VI 64	I
5.	I	V	III	I64	*ii64*	I64	V
6.	I	IV	VI64	I6	*ii6*	iii6	vi
7.	I	V64	I6	III	I6	*ii6*	iii
8.	I	IV	VI	IV	iii6	*ii64*	I

Fig. 15 illustrates an example of the chord progression from Category 3.
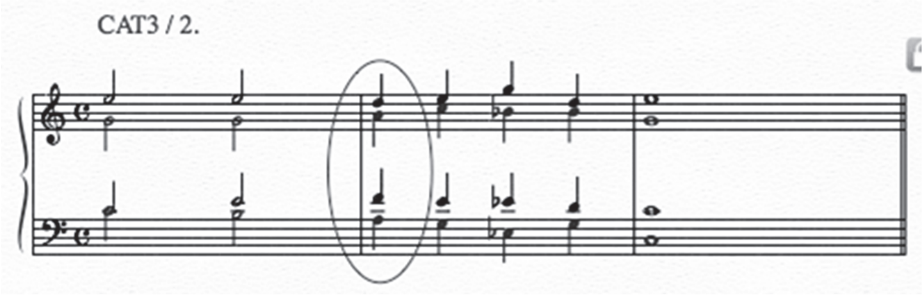
Fig. 15. A sheet music example of a chord progression from Category 3.

The keys of chord progressions from Category 1, 2, and 3 in original order were selected according to the next chain of keys: C–Eb–Gb–A–C–Ab–E–C–Bb–D–Ab–E–Gb–C–Db–B–D–Bb–Eb–A–E–Ab–F–G–Gb–C–G–F–Ab–E–A–Eb–Bb–D–B–Db–C–Gb–F–G. The idea was to assemble the suitable key for every chord progression and look after the variety of keys to avoid the possible fatigue to certain keys. After this was done, the order of experiment trials (chord progressions from Category 1, 2, and 3) were randomized. At the same time, the order of keys collapsed again. The full score of the chord progressions of Experiments 1 is presented in Appendix 6.

There are only pure minor and major triads surrounding the mistuned second-degree triad (by a syntonic comma). Table 18 presents the final experiment order, the location of the mistuned triad, minor and major triads, category, and the key.

Table 18. Location of syntonic comma, pure minor and major triads, key, and category of chord progressions for Experiment 1.

Sample	3rd triad	4th triad	5th triad	6th triad	Key	Category
1	major	major	SC[1]	minor	Gb	CAT3/6
2	minor	SC	major	major	Bb	CAT1/9
3	SC	minor	major	major	Bb	CAT3/1
4	major	major	SC	minor	Gb	CAT2/9
5	SC	major	major	major	Db	CAT1/15
6	SC	minor	major	minor	Eb	CAT2/3
7	major	minor	SC	minor	C	CAT1/8
8	minor	major	minor	SC	A	CAT2/15
9	minor	major	major	SC	Ab	CAT2/13
10	major	SC	major	major	G	CAT2/8
11	major	major	SC	major	C	CAT3/5
12	major	major	minor	SC	G	CAT3/8
13	SC	minor	major	major	D	CAT2/1
14	SC	major	major	minor	D	CAT3/2
15	major	minor	minor	SC	C	CAT1/1
16	minor	major	major	SC	Gb	CAT1/3
17	minor	SC	minor	major	F	CAT2/7
18	major	minor	SC	minor	G	CAT2/11
19	major	major	SC	major	E	CAT 1/7
20	major	major	major	SC	Eb	CAT2/16
21	major	SC	minor	major	D	CAT1/10
22	minor	major	major	SC	Eb	CAT1/2
23	major	SC	minor	major	E	CAT2/5
24	SC	major	major	minor	Gb	CAT1/13
25	major	SC	major	major	Ab	CAT1/11
26	minor	minor	SC	major	C	CAT1/5
27	SC	major	major	minor	Bb	CAT2/2
28	major	SC	minor	major	B	CAT3/3
29	SC	minor	minor	major	C	CAT1/14
30	SC	major	major	major	A	CAT2/4
31	major	major	major	SC	F	CAT3/7
32	major	minor	SC	major	C	CAT2/10
33	minor	SC	major	major	Ab	CAT2/6
34	SC	minor	minor	major	B	CAT1/16
35	major	major	SC	minor	Ab	CAT1/6
36	major	minor	minor	SC	A	CAT1/4
37	minor	SC	minor	minor	E	CAT1/12
38	major	SC	major	major	Db	CAT3/4
39	major	major	SC	major	F	CAT2/12
40	major	major	minor	SC	E	CAT2/14

[1] SC = syntonic comma

3.2.3 Design

The dependent variable in all of the following will be ”recognition of mistuning”—understood simply as the percentage of correct identifications of the target triad. The first variable is 1) recognition of mistuning in the whole data set (40 chord progressions). The next variable is 2) differences in recognition of mistuning between separate locations of the mistuned triad.

Participants’ ability to recognize a mistuned triad in tonal environments representing varying levels of harmonic complexity is the following issue. Thus, the next three dependent variables are 3) recognition of mistuning in Category 1 (The mistuned ii triad between triads representing iii and I), 4) recognition of mistuning in Category 2 (The mistuned ii degree triad between triads representing I, iii, IV, and vi), and 5) recognition of mistuning in Category 3 (modal alterations, the mistuned ii degree triad between triads representing iii/III and I), 6) mistuning recognition, the syntonic comma in melodic movements**.**

False judgments in participants’ answers were divided between purely tuned minor and major triads. Thereby there are eight dependent variables more: 7) mistuning misattributions to a minor triad, 8) mistuning misattributions to a minor triad in Category 1, 9) mistuning misattributions to a minor triad in Category 2, 10) mistuning misattributions to a minor triad in Category 3, 11) mistuning misattributions to a major triad, 12) mistuning misattributions to a major triad in Category 1, 13) mistuning misattributions to a major triad in Category 2, and 14) mistuning misattributions to a major triad in Category 3.

Finally, an important goal was to examine whether and how a certain musical background would affect the listener’s ability to recognize a mistuned triad. This was done by the following independent variables: the instrument group, choir voice, and the duration of playing the main instrument. In addition, there were age and gender as stabilized variables.

3.2.4 Procedure

Listener’s ability to perceive mistuned ii triad in three categories representing three different stages of harmonic complexity is the focus of this experiment. Given that participants could only single out one mistuned chord for each chord progression, there is no need for a more sophisticated measure that would treat ”misses” and ”false alarms” separately. The influence of the location of the mistuned target triad also interested the author. The design of the influence of certain background variables is presented in Sub-chapter 2.5.

The participants were tested in small groups ($N = 7$–11), with each of them wearing headphones. There were 11 sets of similar headphones available (Shure SRH 440), and thus a maximum of 11 participants could complete the experiment at the same time. The number of participants running the experiment varied depending on the circumstances. The samples were played back on a CD player (Sony CDP-212, with Behringer Powerplay Pro-XL, four-channel High-Power Headphones Mixing and Distribution Amplifier, Model HA 4700). The volume was adjusted to a comfortable listening level, keeping it exactly on the same level for all participant groups. Given the measures taken, the small groups will have no practical significance for the research, and the participants may thus in the following be treated as one larger group.

In the beginning of the session, a questionnaire was filled out on the front page of the response packet (see Appendix 1). After this, they received spoken instructions for the test. The content of these instructions was also summarized in the response packet. When the experiment began with the CD, the instructions were repeated through headphones, followed by one practice chord progression.

After this, in each of the 40 chord progressions, the participants' task was to listen very carefully to triads number 3–6. They were asked to write down to the paper, which of these four triads sounded "most out of tune, mistuned, false."

The 40 triadic progressions were performed twice. The duration of each chord progression was 12 seconds. It took approximately 35 seconds to play one triadic progression twice with necessary rests. Between chord progressions (performed twice), the number of the next sample was announced spoken. The CD performed in the experiment had a duration of approximately 24 minutes. With auditory instructions given by the researcher, the total duration of the experiment was approximately 30 minutes. Instructions for the youngest participants took, of course, some more time. All the experiments were executed during the one school lesson (45 minutes) scheduled for the pupils at music class in comprehensive school, primary education (third, fourth, fifth, and sixth grades).

3.2.5 Data analysis

The basis of statistical data processing in the confidence interval for M was ($p = 0.05$, CI = 95%). However, there were comparisons of several sum variables. Because of this, Bonferroni corrections were calculated so that the CI was 98.3%

for three variables and 99.5% for four variables, resulting in a 95% confidence level over all comparisons. The differences in recognition of mistuning between Categories 1, 2, and 3 in relationship with descriptive values were tested (CI = 98.3%, bootstrap).

The bootstrap method is sampling with replacement, and it gives simulated data of the original size. The same observation can appear several times in simulated data. Bootstrapping calculates the value of every bootstrap sample separately (Davison & Hinkley, 1997, p. 507).

Most of the multidimensional analyses with background variables were done using both parametric and nonparametric tests, because the frequency distributions were both normally and non-normally distributed. The reliabilities of mistuning misattributions to a minor triad and major triad in three categories were quite low, and this is the reason for giving up reporting results from those three categories of misattributions. We performed a series of EFAs, starting with a tethracoric correlation matrix to examine the undedlying factorial structure of the variables corresponding to test items. Factor analysis was, therefore, part of the validity evaluation. Based on the results of EFAs, we created three sum variables that were used as dependent variables at the end of the experiment in Sub-chapter 3.4.1. As all the variables corresponding to the test items were binary, we used tetrachoric correlation matrices as starting points for each EFA. The tetrachoric correlation is, essentially, an estimate of the product–moment correlation that would have been obtained with the underlying continuous variables if their joint distribution was bivariate normal (see Lorenzo-Seva & Ferrando, 2012).

The one-way ANOVA (with Bonferroni post hoc test, when necessary) test was used with the *instrument group* variable and *choir voice* variable. Also, the nonparametric Kruskal–Wallis test was used with the *instrument group* variable and *choir voice* variable: Pairwise comparisons were done using the Dunn test. The analyses with *gender* variables were done using the independent samples t test and nonparametric Mann–Whitney U test.

The analyses with *instrumental experience* variable and *age* variable were done using the regression analysis with the supposition that all connections will not necessarily come out. Correlations between dependent variables and *instrumental experience* variable and *age* variable were done using the nonparametric Spearman's ρ because of non-normal distributions.

The validity analyses were conducted through factor analysis with the maximum likelihood and varimax methods. The reliability analyses were conducted using Cronbach's α.

3.3 Results

The results of Experiment 1 are introduced detailly in the following sub-chapters. Recognition of mistuning, on the whole, is presented in Sub-chapter 3.3.1. The location of the mistuned triad is handled in Sub-chapter 3.3.2. Mistuning misattributions are in focus in Sub-chapter 3.3.3. The influence of background variables includes in Sub-chapter 3.3.4. Finally, Sub-chapter 3.3.5 includes music-analytical observations.

3.3.1 Recognition of mistuning throughout the complete data set and in categories

As already explained, this experiment used 40 chord progressions that all included one triad mistuned by the syntonic comma. As seen in Fig. 16, the number of correctly recognized mistuned chords (SC_All) varied from 8 to 35 ($M = 22.97$, SD = 5.78, median = 24). The distribution did not obey the normal distribution according to the Kolmogorov–Smirnov test [K–S(154) = .103, $p < .001$] and Shapiro–Wilk [S–W(154) = .98, $p < .05$] and it was slightly skewned to the left (skewness = −.26, C.R. = −1.35). Kurtosis (−.63, C.R. = −1.63) was clearly negative.

Out of the 166 participants in this experiment, 12 participants had at least one missing response and were discarded from the analysis. The results were analyzed for the remaining 154 participants who both completed the background information and responded to all 40 chord progressions in the main experiment. The number of participants changed between the individual categories.

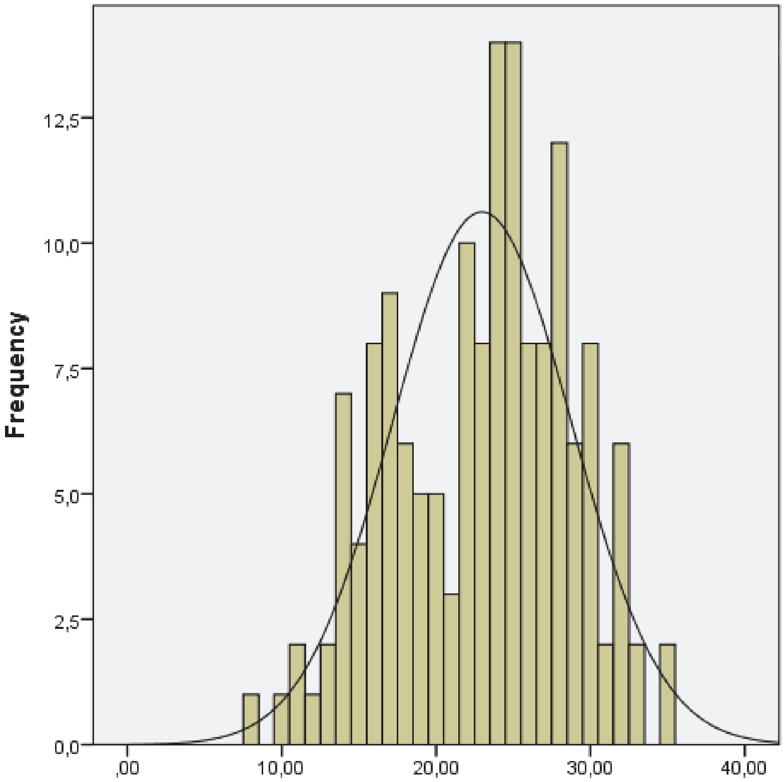

Fig. 16. The distribution of correct recognitions of mistuning in Experiment 1. Horizontal axis = correct responses. Vertical axis = number of participants.

Category 1 (ii triad between triads representing I and iii)

The participants succeeded best in Category 1, with three of them even responding correctly for all of the 16 chord progressions seen in Fig. 17. The observed frequencies nevertheless ranged between 4 and 16, and the median was 11 ($M = 10.68$, SD = 2.84). The distribution had a clearly negative kurtosis (= −.79, C.R. = −2.04), which can be regarded as significantly different from 0 (C.R. < −1.96). The distribution did not obey the normal distribution [K–S(155) = .10, $p < .01$] and [S–W(155) = .97, $p < .01$] and it was a bit skewed to left (skewness = −.20, C.R. = −1.04). There was a sort of bump in the distribution at 14 correct identifications (20 participants). The range of recognition was 12 (4–16).

There were 2480 observed values in Category 1 ($N = 155$). No less than 66.77% of the mistuned triads were recognized (1656 of 2480).

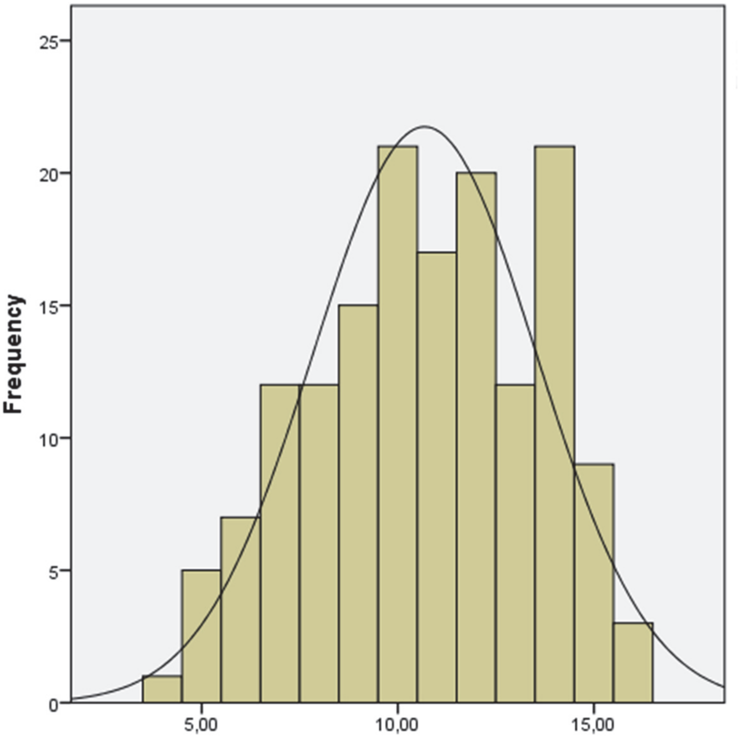

Fig. 17. The distribution of correct recognitions of mistuning in Category 1. Horizontal axis = correct responses. Vertical axis = number of participants.

Category 2 (ii triad between triads representing I, iii, IV, and vi)

The chord progressions in Category 2 seemed appreciaply more demanding than those in Category 1. The range of frequencies (12) was the same as in Category 1, but at a lower level (from 2 to 14), as shown in Fig. 18. Median was 9, and there was a small bump in the distribution at 9 and 10 recognitions ($M = 8.65$, SD = 2.38). Category 2 was not normally distributed [K–S(162) = .14, $p < .001$] and [S–W(162) = .97, $p < .01$] and the distribution was perceptibly skewed to the left (skewness = −.35, C.R. = −1.82). Kurtosis was practically neutral (= .09, C.R. = .02). There were 2592 observed values in Category 2 (*N*=162). The participants recognized 54.1% of mistuned triads (1402 of 2592).

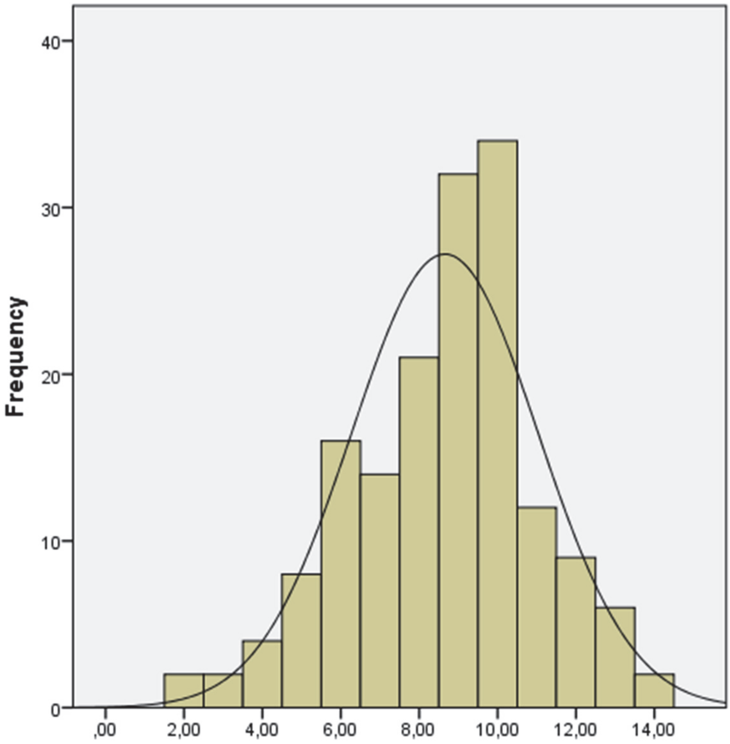

Fig. 18. The distribution of correct recognitions of mistuning in Category 2. Horizontal axis = correct responses. Vertical axis = number of participants.

Category 3 (modal alterations, ii triad between triads representing I and iii)

The third category was the most demanding part of the experiment (see Fig. 19). The range of correct responses was as wide as it could be (0–8), but the distribution is clearly skewed to the right (skewness = .40, C.R. = 2.09) which differs significantly from 0 (C.R. > 1.96). Normality tests [K–S(165) = .15, $p < .001$] and [S–W(165) = .95, $p < .001$] confirm this. The distribution had a notable value of kurtosis (−.62, C.R. = −1.66). There was a bump at 2, and the median remaining quite low, 3 (*M* = 3.41, SD = 1.96). There were 1320 observed values in Category

3 (N = 165). The participants recognized 42.6% of mistuned triads (562 of 1320). The range of recognition was as wide as it can be: 0–8.

It is presumable that modally altered chords (the III and VI triads) have been experienced as mistuned, although they were purely intonated. This issue is viewed later on in Sub-chapter 3.3.5.

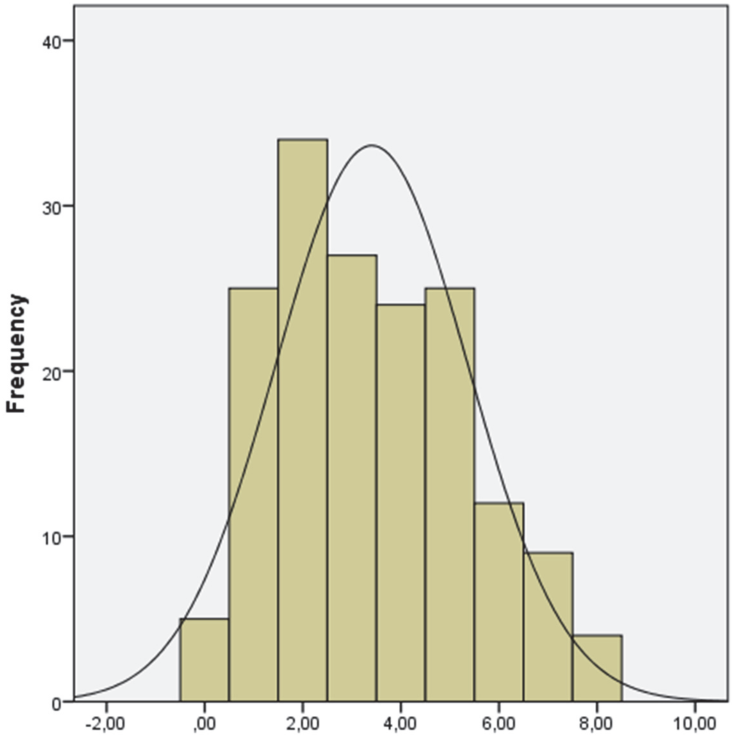

Fig. 19. The distribution of correct recognitions of mistuning in Category 3. Horizontal axis = correct responses. Vertical axis = number of participants.

Differences between categories in recognition of mistuning

As explained earlier, the categories were generated on the basis of music theory considerations. Category 1 included the mistuned ii triad between triads representing I and iii degrees. Category 2 included the mistuned ii triad between triads representing I, iii, IV, and vi. Category 3 included modal alterations, and the mistuned ii triad was performed between triads representing I and iii. The complexity of musical texture grows from Category 1 through Category 2 to Category 3. These three categories seem to have produced different results in recognition of mistuning. The growing complexity seemed to complicate the recognition of the target.

As remembered, there were 16 chord progressions in Category 1, 16 chord progressions in Category 2, and 8 chord progressions in Category 3. Because there were only 8 chord progressions in Category 3, linear transformation from 8 to 16 had to be done. It was calculated by the following formula: $y = 2x$. The sum variable used in this context was simply created by multiplying the frequencies of Category 3 by 2. Table 19 shows the differences between categories concerning means, medians, and confidence intervals of means and medians ($N = 154$).

Table 19. Values and confidence interval of means and median of mistuning recognition in Categories 1, 2, and 3.

Variables	*M*[1] Max 16.00	Confidence intervals of means: CI[2] = 98.3% (bootstrap)		Mdn[3]	Confidence intervals of medians: CI = 98.3% (bootstrap)		SD[4]	Confidence intervals of standard deviations: CI = 98.3% (bootstrap)	
		lower	upper		lower	upper		lower	upper
CAT1	10.69	10.16	11.23	11.00	10.00	12.00	2.85	2.55	3.15
CAT2	8.79	8.34	9.22	9.00	9.00	9.00	2.27	1.95	2.58
CAT3	6.99	6.18	7.74	6.00	6.00	8.00	3.97	3.51	4.40

[1] *M* = mean, [2] CI = confidence interval, [3] Mdn = median, [4] SD = standard deviation

These findings confirmed the differences between the three categories. The confidence intervals of means and medians of separate categories did not overlap. It can be claimed (with a grain of salt) that the locations of the distributions were distinct. Concerning the confidence intervals of SD, Category 1 and 2 barely overlap, but Category 3 was clearly different.

Category 2 split into two sets

There were 10 chord progressions that included syntonic commas in melodic movements in addition to the mistuned ii triad. These chord progressions have been introduced in Sub-chapter 3.2.2. All of these chord progressions belonged to Category 2. The observed frequencies ranged between 1 and 10, and the median was 6 ($M = 5.91$, $\mathrm{SD} = 1.90$). The distribution was clearly skewed to the left (skewness $= -.43$, C.R. $= -2.23$) which can be regarded as significantly different from 0 (C.R. < -1.96). So, because of skewness, the distribution did not obey the normal distribution [K–S(162) = .16, $p < .001$] and [S–W(162) = .96, $p < .001$]. There were 1620 observed values in this area (N = 162) and the listeners recognized 958 of them (59.1%). Kurtosis was close to neutral (−.13, C.R. = −0.33). As mentioned earlier, the participants recognized a total of 54.1% of mistuned triads (1402 of 2592) in Category 2.

In comparison, there were six chord progressions that did not include a syntonic comma in melodic movements. The observed values ranged from 0 to 5 (from a total of six) (M = 2.74, median = 2.91, SD = 1.11). The participants recognized 452 of the total 972 observed values (46.50%). The distribution did not obey the normal distribution according to the Kolmogorov–Smirnov test [K–S(165) = .17, $p < .001$] and Shapiro–Wilk [S–W(165) = .93, $p < .001$] and it was slightly skewed to left (skewness = .10, C.R. = 0.55). Kurtosis (−.36, C.R. = −.033) was perceptibly negative.

Thus, Category 2 was split into two, and the following results are actually presented in four categories. It is very important to remember that the participants were asked to listen to harmonic mistuning in one triad of four possible.

Differences between four categories (Category 2 split in two)

Because of the differences between chord progressions (A syntonic comma in melodic movements in category and chord progressions without melodic commas in Category 2, the next analysis was done between four sum variables: A) Category 1, B) chord progressions (a syntonic comma in melodic movements in Category 2, C) chord progressions without melodic commas in Category 2, and D) Category 3 in recognition of mistuning.

The difference between B) chord progressions (A a syntonic comma in melodic movements in Category 2), and C) chord progressions without melodic commas in Category 2) was so clear that it was justifiable to compare these two groups with Category 1 and Category 3. To make this happen, it was necessary to create linear transformations to sum variables of B, C, and D groups (16 chord progressions for each). Mistuning recognition between these four groups in relationship with descriptive values was tested (CI = 98.3%, bootstrap). The values are gathered in Table 20 (N = 154).

Table 20. Values and confidence intervals of means and median for mistuning recognition in four categories (Category 2 split in two).

Variables	*M* [1] Max 16.00	Confidence intervals of means: CI[2] = 99.2% (bootstrap)		Mdn[3]	Confidence intervals of medians: CI = 99.2% (bootstrap)		SD[4]	Confindence intervals of standard deviations: CI = 99.2% (bootstrap)	
		lower	upper		lower	upper		lower	upper
CAT1	10.69	10.07	11.29	11.00	10.00	12.00	2.85	2.53	3.19
CAT2 mel.	9.64	9.02	10.28	9.60	9.60	11.20	2.89	2.45	3.34
CAT2 no mel.	7.34	6.77	7.98	8.00	5.33	8.00	2.94	2.51	3.33
CAT3	6.99	6.04	7.81	6.00	6.00	8.00	3.97	3.46	4.44

[1] *M* = mean, [2] CI = confidence interval, [3] Mdn = median, [4] SD = standard deviation

Mistuning was detected best in A) Category 1. The set B (melodic commas) was rather close to set A. In the set of chord progressions without melodic commas (C), mistuning was recognized as essentially worse. The worst result occurred in Category 3 (D), which was practically equal to Group C.

The confidence intervals of means and medians did not overlap between Category 1 and Category 2 (no melodic commas), between two groups of Category 2, between Category 2 (melodic commas), and Category 3. The confidence intervals of SD did not overlap between Category 2 (melodic commas) and Category 3. As an unavoidable consequence of these results, the values did not overlap between Category 1 and 3, either. It can even be claimed that the locations of the distributions were distinct.

3.3.2 Locations of the mistuned triad

Mistuning recognition between the four locations in relationship with descriptive values was tested (CI = 99.2%, bootstrap). The values are gathered in Table 21 ($N = 154$).

Table 21. Values and confidence intervals of means and medians with recognition of mistuning in separate locations of the mistuned triad.

Variables	*M*[1] Max 10.00	Confidence interval of means: CI[2] = 99.2% (bootstrap)		Mdn[3]	Confidence interval of medians: CI = 99.2% (bootstrap)		SD[4]	Confidence intervals of standard deviations: CI = 99.2% (bootstrap)	
		lower	upper		lower	upper		lower	upper
Loc. 1	5.82	5.32	6.30	6.00	5.00	7.00	2.36	2.06	2.64
Loc. 2	5.32	4.90	5.72	5.00	5.00	6.00	1.95	1.70	2.20
Loc. 3	6.11	5.83	6.43	6.00	6.00	7.00	1.36	1.14	1.56
Loc. 4	5.72	5.31	6.11	6.00	5.00	6.00	1.88	1.60	2.14

[1] *M* = mean, [2] CI = confidence interval, [3] Mdn = median, [4] SD = standard deviation

When the mistuned triad was in Location 3, it was detected best. Location 1 and Location 4 were practically equal. Both locations were not far away from Location 3. Location 2 was clearly the worst for recognizing mistuning. There was an essential difference only between Locations 2 and 3 according to confidence interval analysis (bootstrap). The confidence intervals of means and SDs did not overlap between Location 2 and Location 3. It can be claimed that the locations of the distributions were distinct. In addition, the confidence interval of SDs did not overlap between Locations 3 and 4.

The explanation for this phenomenon is difficult to find. One possible explanation for these differences is accented tones. The tones in Locations 1 and 3 are in principle accented tones of chord progression. These findings do not give a reason to report further results by location.

3.3.3 Mistuning misattributions to a minor and major triad

The experiment was constructed so that participants had to choose between one of four alternatives. If they did not recognize the mistuned triad (the triad with the syntonic comma), there would only be pure minor triads and pure major triads left. One might therefore ask how often the participants might have misattributed mistuning to minor triads and how often to major triads. Misattributions to a minor triad are more understandable because the intervals of a pure major triad come from harmonic spectra. Mistuning was misattributed to a minor triad in 18.85% of cases (1161 of 6160) ($M = 7.54$), and to a major triad in 23.73% of cases (1462 of 6160) ($M = 9.49$). However, these values are not comparable: besides the mistuned second-degree triad, there were more major triads (79) than minor triads (43) as potential receivers of the misattribution. Indeed, there were 10 chord progressions without any minor triad and one chord progression without any major triad. There were only 29 experiment items where all alternatives (syntonic comma, minor triad, major triad) were available. Hence, it is with reference to these 29 cases that the question concerning misattributions to major and minor may be more relevantly raised. However, there are only four triads to be listened to, one of them being the mistuned target. There are either two minor triads and one major triad or two major triads and one minor triad. The number of minor triads was 39, and the number of major triads was 48. So, it is necessary to react very critically to the results of misattributing to a minor and to a major triad.

Mistunings were misattributed most often to minor triads, although there were 39 minor triads against 48 major triads in 29 experiment items ($N = 156$). The distribution of frequencies is seen in Fig. 20. Misattributions to a minor triad were not normally distributed [K–S(156) = .1, $p < .001$] and [S–W(156) = .98, $p < .05$] with the range of 1–14. There was a bumb in distribution of eight misattributions ($M = 7.17$, SD =2 .62, median = 7, Mode = 8). The distribution was minimally skewed to the right (skewness = .08, C.R. = .40) while kurtosis was negative (= −.38, C.R. = −.99).

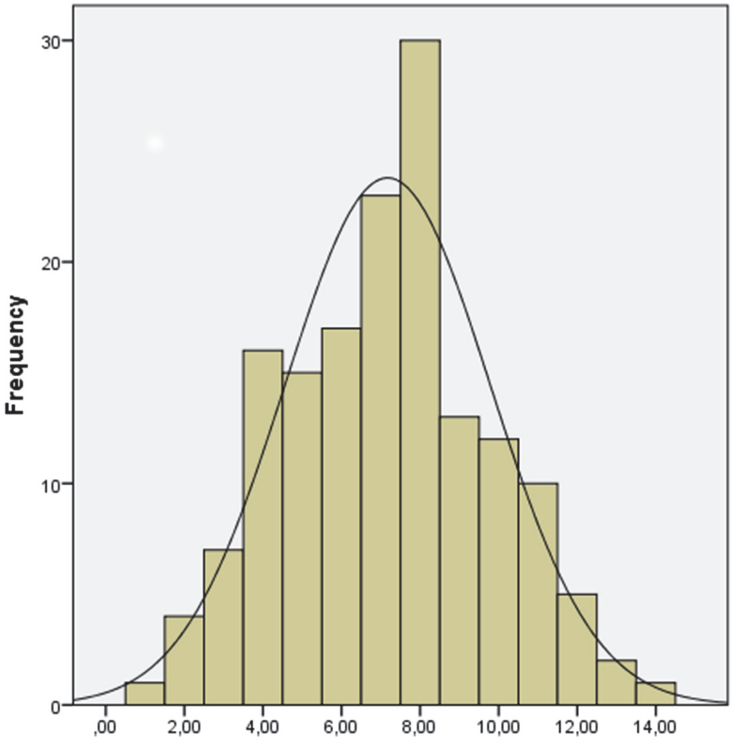

Fig. 20. The distribution of frequencies mistuning that was misattributed to minor triad in 29 experiment items. Horizontal axis = correct responses. Vertical axis = number of participants.

There were 48 major triads in 29 experiment items. The distribution of frequencies of mistuning was misattributed to a major triad is clearly skewed to the right (skewness = .95, C.R. = 4.91) which differs significantly from 0 (C.R. > 1.96). So, it was not normally distributed [K–S(156) = .14, *p* < .001] and [S–W(156) = .94, *p* < .001]. Also kurtosis (= 1.01, C.R. = 2.82) was significantly different from 0 (C.R. > 1.96). There were two participants who never misattributed mistuning to a major triad. Nine participants misattributed once (*N* = 156). 51.3% of participants misattributed mistuning to a major triad 2–5 times of total 29 experiment items. Two outliers misattributed mistuning to a major triad as many as 17 times. The range was broad: 0–17 (*M* = 5.47, SD = 3.23, median = 5, Mode = 3). The distribution of frequencies is seen in Fig. 21.

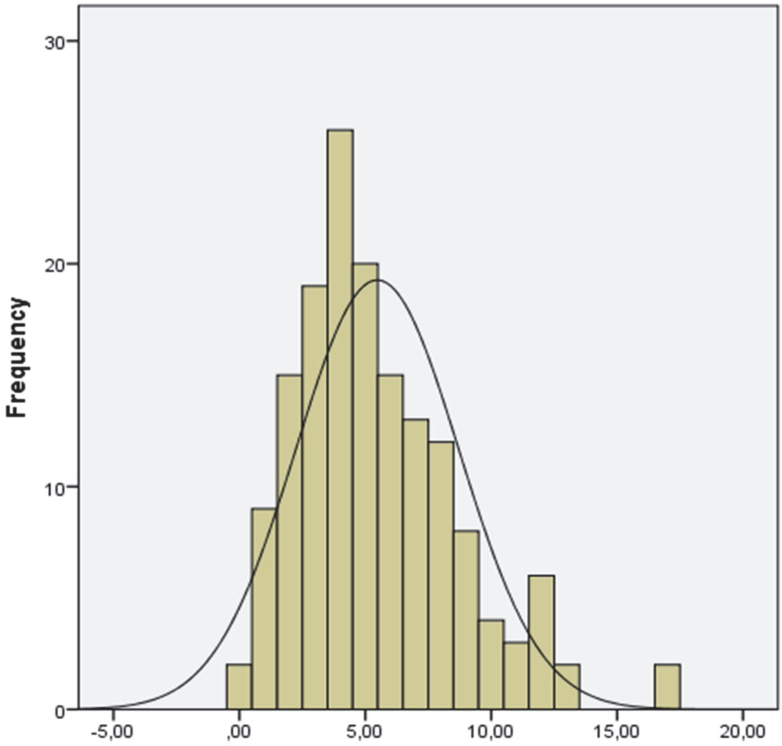

Fig. 21. The distribution of frequencies mistuning was misattributed to major triad in 29 experiment items. Horizontal axis = correct responses. Vertical axis = number of participants.

Mistuning was misattributed to a minor triad almost three times more often than to a major triad in Category 1. In Category 2, the difference is much smaller (3.72 and 2.04). A remarkable change comes in Category 3: Mistuning misattributions to a major triad is six times more frequent than to a minor triad. None of the distributions in these six cases were normally distributed according to the Kolmogorov–Smirnov test and Shapiro–Wilk test (for all, $p < .001$). The values of test statistics and degrees of freedom were gathered into the table, which is seen in Table 42 in Appendix 9 (The normality tests of mistuning misattributions to a minor triad and major triad in three categories in Experiment 1).

The differences between categories in mistuning misattributions to a minor triad and major triad

Mistuning was misattributed to a minor triad in 24.73% of cases (1,119 of 4,524) (*M* = 7.17), and to a major triad in 18.88% of cases (854 of 4,524) (*M* = 5.47).

There were 12 experiment items in Category 1, 12 experiment items in Category 2, and five experiment items in Category 3 in the data set (29 experiment items). This condensed data set makes it possible to find out if there were differences between categories in misattributions to a minor triad and to a major triad. To make this happen, it was necessary to create a linear transformation to sum variables of mistuning misattributions to a minor triad in Category 3 and mistuning misattributions to a major triad in Category 3 to get 12 chord progressions also for Category 3.

The differences in mistuning misattributions to a minor triad between Category 1, 2, and 3 in relationship with descriptive values were tested (CI = 98.3%, bootstrap). The values are gathered in Table 22 (*N* = 156).

Table 22. Values and confidence interval of means and medians in mistuning misattributions to a minor triad in Categories 1, 2, and 3.

Variables	*M*[1] Max 12.00	Confidence intervals of means: CI[2] = 98.3% (bootstrap)		Mdn[3]	Confidence intervals of medians: CI = 98.3% (bootstrap)		SD[4]
		lower	upper		lower	upper	
CAT1	2.98	2.67	3.30	3.00	3.00	4.00	1.66
CAT2	3.72	3.42	4.01	4.00	3.00	4.00	1.59
CAT3	1.14	.89	1.43	.00	.00	2.40	1.45

[1] *M* = mean, [2] CI = confidence interval, [3] Mdn = median, [4] SD = standard deviation

The confidence intervals of means did not overlap between Category 1 and 2, between 2 and 3, and between 1 and 3. The confidence intervals of medians did not overlap between 1 and 3 and between 2 and 3. It can be claimed that the locations of the distributions were distinct.

Similarly, the differences in mistuning misattributions to a major triad in between Category 1, 2, and 3 in relationship with descriptive values were tested (CI = 98.3%, bootstrap). The values are gathered to Table 23 (*N* = 156).

Table 23. Values and confidence interval of means and median for mistuning misattributions to a major triad in Categories 1, 2, and 3.

Variables	*M*[1] Max 12.00	Confidence intervals of means: CI[2] = 98.3% (bootstrap)		Mdn[3]	Confidence intervals of medians: CI = 98.3% (bootstrap)		SD[4]
		lower	upper		lower	upper	
CAT1	1.10	.85	1.38	1.00	.00	1.00	1.42
CAT2	1.99	1.76	2.24	2.00	2.00	2.00	1.28
CAT3	5.71	5.12	6.35	4.80	4.80	7.20	3.33

[1] *M* = mean, [2] CI = confidence interval, [3] Mdn = median, [4] SD = standard deviation

Concerning mistuning misattributions to a major triad, the confidence intervals of means and medians did not overlap between Category 1 and 2, between 2 and 3, and between 1 and 3. It can quite securely be claimed that the locations of the distributions were distinct. Category 3 is a special one; misattributions to a major triad differed clearly from other categories: Modally altered, but vertically pure major triads have likely mislead several participants.

3.3.4 Background variables

As remembered, there were some background variables in this experiment. Those variables were the instrument group, choir voice, and the duration of playing the main instrument. In addition, there were age and gender as stabilized variables.

Recognition of mistuning by instrument groups, choir voices, and gender

Recognition of mistuning by instrument group is presented in Table 24.

Table 24. Recognition of mistuning, by instrument groups.

Instrument group	Data set: 40 trials *N* = 153		CAT1 16 trials *N* = 154		CAT2 16 trials *N* = 161		CAT3 8 trials *N* = 164		Mel. commas (CAT2): 10 trials *N* = 161	
	M[1]	SD[2]	*M*	SD	*M*	SD	*M*	SD	*M*	SD
String	23.59	5.55	11.17	3.01	8.75	1.89	3.25	1.75	5.83	1.79
Woodwind	22.74	5.42	10.58	2.60	8.50	2.26	3.41	1.93	5.88	1.68
Brass	20.94	6.80	9.49	2.65	7.94	3.21	2.94	2.13	5.35	2.64
Piano etc.	23.44	5.70	10.47	2.79	8.96	2.23	3.72	2.18	6.27	1.84

[1] *M* = mean, [2] SD = standard deviation

Because of both normal and non-normal distributions (the values are shown in Table 43, Appendix 10), the analysis was carried out both with one-way ANOVA and nonparametric Kruskal–Wallis test. There were no significant differences between how well participants representing different instrument groups succeeded in recognizing the target. This was true in the whole data set and separately for each of the stimulus Categories 1–3 and within the melodic commas group (for all, $p > .05$).

The participants were asked which of the following voice they sing in choirs: top voice (which often sings the melody line), middle voice or bass voice of choir texture. Mistuning recognition by choir voices is presented in Table 25.

Table 25. Mistuning recognition, by choir voices.

Choir voices	Data set: 40 trials $N = 152$		CAT1 16 trials $N = 153$		CAT2 16 trials $N = 160$		CAT3 8 trials $N = 163$		Mel. commas (CAT2) 10 trials $N = 160$	
	M[1]	SD[2]	M	SD	M	SD	M	SD	M	SD
Top voice	21.52	6.05	10.21	2.96	8.18	2.44	3.13	2.08	5.42	2.04
Middle voice	23.47	5.59	10.95	2.98	8.89	2.08	3.63	1.90	6.05	1.85
Bass voice	24.15	5.49	10.92	2.53	9.46	2.16	3.77	1.98	6.38	1.67

[1] M = mean, [2] SD = standard deviation

Because of both normal and non-normal distributions (the values are shown in Table 44, Appendix 11), the multidimensional analysis was carried out both with one-way ANOVA and nonparametric Kruskal–Wallis test.

There were no statistically significant differences between choir voices in recognition of mistuning (ANOVA) and in Category 1 and Category 3, either. This result was also confirmed with the Kruskal–Wallis test (for all, $p > .05$). However, in Category 2, ANOVA showed a statistically significant difference [F (2, 157) = 4.85, $p < .01$] between choir voices, which was also confirmed by a Kruskal–Wallis test [χ^2 (2) = 7.60, $p < .05$]. Further analyses revealed that bass voice singers scored higher than top voice singers in recognition of mistuning ($z = -2.70$, $p < .01$).

In the set of melodic commas, there was a statistically significant difference between top voice singers and bass voice singers according to ANOVA [F (2, 157) = 3.36, $p < .05$]. The same difference was seen in the Kruskal–Wallis test [χ^2 (2) = 6.32, $p < .05$]. Further analyses revealed that bass voice singers scored higher than top voice singers in recognition of mistuning ($z = -2.37$, $p < .05$). Recognition of mistuning by gender is presented in Table 26.

Table 26. Recognition of mistuning, by gender.

Gender	Data set: 40 trials *N* = 154		CAT1 16 trials *N* = 155		CAT2 16 trials *N* = 162		CAT3 8 trials *N* = 165		Mel. commas (CAT2) 10 trials *N* = 162	
	M[1]	SD[2]	*M*	SD	*M*	SD	*M*	SD	*M*	SD
Male	22.14	6.10	10.29	2.74	8.67	2.62	3.18	2.01	5.50	2.25
Female	23.38	5.60	10.88	2.90	8.84	2.09	3.65	1.96	6.12	1.67

[1] *M* = mean, [2] SD = standard deviation

Because of dispersion of both normal and non-normal distributions (the values are shown in Table 45, Appendix 12), the analysis was carried out using both the independent samples t test and the nonparametric Mann–Whitney U test. According to the independent samples t-test, there were no statistically significant differences between male and female participants in recognition of the mistuning. There were also no significant differences in Categories 1 and 3 (for all, $p > .05$). Interestingly, there was a significant difference between male and female participants in Category 2 [$t(160) = -1.01$, $p < .01$]. According to the Mann–Whitney U test, there were no statistically significant differences between male and female listeners in recognition of mistuning, nor in separate categories (for all, $p > .05$). Therefore, it cannot be said reliably that there were differences by gender.

Following the result of Category 2, there was a significant difference between male and female participants in the set of melodic commas [$t(160) = -1.98$, $p < .01$] according to independent samples t test. The mann–Whitney U test did not confirm this result ($p > .05$). Hence, it cannot be said reliably that there were differences by gender.

Mistuning misattributions to a minor triad and major triad by instrument groups, choir voices and gender (data set: 29 experiment items)

Mistuning misattributions to a minor triad and major triad by instrument group, choir voices, and gender are presented in Table 27.

Table 27. Mistuning misattributions to a minor or major triad, by instrument, choir voice, and gender.

Instrument group by Choir voice and by Gender	Mistuning misattributions to a minor triad, data set: 29 trials *M*[1]	SD[2]	Mistuning misattributions to a major triad, data set: 29 trials *M*	SD
Instrument (*N* = 155)				
String	6.82	2.53	5.50	3.32
Woodwind	7.16	2.58	5.55	3.05
Brass	8.24	2.84	6.53	3.87
Piano etc.	7.14	2.64	4.88	2.86
Choir voice (*N* = 154)				
Top voice	7.61	2.47	6.07	3.47
Middle voice	6.80	2.60	5.53	3.42
Bass voice	7.15	2.86	4.64	2.42
Gender (*N* = 156)				
Male	7.62	2.47	6.04	3.76
Female	6.94	2.67	5.18	2.90

[1] *M* = mean, [2] SD = standard deviation

Because of both normal and non-normal distributions concerning mistuning misattributions to a minor triad and major triad by instrument groups and choir voices, the multidimensional analysis was carried out both with one-way ANOVA and nonparametric Kruskal–Wallis test.

There were no statistically significant differences between instrument groups in mistuning misattributions to a minor triad (ANOVA) ($p > .05$). There were no statistically significant differences between instrument groups in mistuning misattributions to a major triad, either. Both results were also true according to the Kruskal–Wallis test (for all, $p > .05$).

There were no statistically significant differences between choir voices in mistuning misattributions to a minor triad (ANOVA). There was the same situation with major triads. The Kruskal–Wallis test confirmed these results (for all, $p > .05$).

When it comes to misattributions to a minor triad and major triad by gender, a dispersion of both normal and non-normal distributions was found. The analysis was carried out using both the independent samples t test and the nonparametric Mann–Whitney U test.

According to the independent samples t test, there were no statistically significant differences between male and female participants in mistuning misattributions to a minor triad or in Category 2 and 3. However, in Category 1, there was a significant difference [$t(156) = 1.29$, $p < .05$]. According to the Mann–

Whitney U test, there were no statistically significant differences between male and female listeners in mistuning misattributions to a minor triad, nor in separate categories (for all, $p > .05$). Thus, it cannot be said reliably that there were differences between male and female participants.

Concerning the misattributions to a major triad, the independent samples t-test showed no statistically significant differences, nor in Category 1 and 3. In the case of Category 2, there was a significant difference [$t(161) = 1.27, p < .05$] between male and female participants. According to the Mann–Whitney U test, there were no statistically significant differences between male and female listeners in mistuning misattributions to a major triad, nor in separate categories (all $p > .05$). In conclusion, it cannot be said reliably that there were differences between male and female participants.

Recognition of mistuning (instrumental experience and age as independent variables)

Several connections were found between recognition of mistuning and instrumental experience and age. The results of the regression analysis are presented in the following. The majority of distributions of recognition of mistuning by instrumental experience and age were normally distributed. Because of some non-normal distributions, the results are acceptable with certain reservations. It is possible that all connections between variables did not appear in these analyses.

Instrumental experience variable and *age* variable are suitable variables for regression analysis. At first, *recognition of mistuning* variable (all recognitions of mistuning in the whole test, 40 experiment items) was set as a dependent variable. *Instrumental experience* variable and *age* variable were set as independent variables.

A simple linear regression was calculated to predict participants' recognition of mistuning based on instrumental experience and age. Instrumental experience and age together explained 29.3% of recognition of mistuning, which can be regarded as notable [$F(2, 146) = 30.30, p < .001$] . When age increased by one year, recognition of mistuning increased by 0.46 unit element ($p < .01$). When instrumental experience increased by one year, recognition of mistuning increased by 0.36 unit element ($p < .05$). Both connections were relatively strong. To put in formula:

Recognition of mistuning = 14.446 + 0.458 × age + 0.355 × instrumental experience

Recognition of mistuning = Recognitions of mistuning in the whole test (40 experiment items)

When *recognition of mistuning in Category 1* variable was set as a dependent variable in regression analysis, instrumental experience and age together explained 14.9% of recognitions of mistuning in Category 1, which can be regarded as perceptible [$F(2, 147) = 12.84$, $p < .001$]. There were no statistically significant connections between recognition of mistuning and instrumental experience and age in Category 1 (both $p > .05$).

When *recognition of mistuning in Category 2* variable was set as a dependent variable, instrumental experience and age together explained 20.7% of recognitions of mistuning in Category 2, which can be regarded as notable [$F(2, 154) = 20.08$, $p < .001$]. When age increased by one year, recognition of mistuning increased by 0.16 unit element ($p < .05$). The connection between recognition of mistuning and instrumental experience was not statistically significant in Category 2 ($p > .05$).

In the case of *recognition of mistuning in Category 3* variable as a dependent variable, instrumental experience and age together explained 24.7% of recognitions of mistuning in Category 3 which can also be regarded as notable [$F(2, 157) = 25.78$, $p < .001$]. When age in Category 3 increased by one year, recognition of mistuning increased by 0.18 unit element ($p < .001$). The connection between recognition of mistuning and instrumental experience was not statistically significant in Category 3 ($p > .05$). To put in formula:

Recognition of mistuning in Category 1 = 7.828 + 0.145 × age + 0.141 × instrumental experience

Recognition of mistuning in Category 2 = 5.706 + 0.160 × age + 0.125 × instrumental experience

Recognition of mistuning in Category 3 = 0.414 + 0.184 × age + 0.073 × instrumental experience

When *recognition of mistuning in melodic commas* variable was set as a dependent variable, instrumental experience and age together explained 23.4% of recognitions of mistuning with this variable, which can be regarded as notable [$F(2, 154) = 23.55$, $p < .001$]. When age increased by one year, recognition of mistuning increased by 0.12 unit element ($p < .05$). When instrumental experience increased by one year, recognition of mistuning increased by 0.12 unit element ($p < .05$). To put in formula:

Mistuning recognition in melodic commas = 3.502 + 0.121 × age + 0.123 × instrumental experience

Mistuning misattributions to a minor triad and major triad (instrumental experience and age as independent variables) (Data set: 29 Experiment items)

With regression analysis, *mistuning misattributions to a minor triad* was set as a dependent variable. Instrumental experience and age together explained 15.4% of mistuning misattributions to a minor triad, which can be regarded as notable [$F(2, 148) = 13.48, p < .001$]. When age increased by one year, misattributions to a minor triad decreased by 0.20 unit element ($p < .01$). The connection between mistuning misattributions to a minor triad and instrumental experience was not statistically significant ($p > .05$). To put in formula:

Mistuning misattributions to a minor triad = 10.369 – 0.202 × age – 0.063 × instrumental experience

(Mistuning misattributions to a minor triad = Mistuning misattributions to a minor triad in data set: 29 items)

With regression analysis, *mistuning misattributions to a major triad* was set as a dependent variable. Instrumental experience and age together explained 24.4% of mistuning misattributions to a major triad, which can be regarded as notable [$F(2, 148) = 23.83, p < .001$]. When age increased by one year, mistuning misattributions to a major triad decreased by 0.20 unit element ($p < .05$). When instrumental experience increased by one year, mistuning misattributions to a major triad decreased by 0.22 unit element ($p < .05$). So, the older and more experienced the participant was, the less he or she misattributed mistuning to a major triad. There was the same phenomenon with misattributions to a minor triad. This, of course, makes sense, because mistuning recognition was clearly connected to the accession of instrumental experience and age. To put in formula:

Mistuning misattributions to a major triad = 9.561 – 0.196 × age – 0.224 × instrumental experience

(Mistuning misattributions to a major triad = Mistuning misattributions to a major triad in data set: 29 items)

Correlations between recognition of mistuning and instrumental experience and age

It seemed reasonable to clarify whether there occurred a correlation between detected mistuning and instrumental experience and detected mistuning and age. As remembered, none of the frequency distributions of recognition of mistuning in the whole data set nor in Category 1, 2, and 3 were normally distributed. Because of this, the analysis of correlations was carried out with nonparametric Spearman's rho correlations. As a result, recognition of mistuning was positively correlated both with the participants' age ($\rho = .48$, $p < .001$, $N = 154$) and with their instrumental experience ($\rho = .46$, $p < .001$, $N = 149$). Age and instrumental experience were strongly correlated ($\rho = .72$, $p < .001$, $N = 161$).

In Category 1, there was a positive correlation between recognition of mistuning and instrumental experience ($\rho = .34$, $p < .001$, $N = 150$) as well as between recognition of mistuning and age ($\rho = .34$, $p < .001$, $N = 155$).

Further, a positive correlation between the recognition of mistuning and instrumental experience ($\rho = .37$, $p < .001$, $N = 157$) and recognition of mistuning and age ($\rho = .39$, $p < .001$, $N = 162$) was found also in Category 2.

In addition, the same situation occurred between the recognition of mistuning and instrumental experience ($\rho = .38$, $p < .001$, $N = 160$) and recognition of mistuning and age ($\rho = .43$, $p < .001$, $N = 165$) also in Category 3. Finally, the recognition of mistuning (a syntonic comma in melodic movements) was positively correlated with the participants' instrumental experience ($\rho = .44$, $p < .001$, $N = 157$) and age ($\rho = .45$, $p < .001$, $N = 162$).

Correlations between mistuning misattributions to a minor and major triad and instrumental experience and age

Further, none of the distributions of mistuning misattributions to a minor triad or major triad, nor in separate categories, were normally distributed. Because of this, nonparametric Spearman's rho correlations were used: There was a negative correlation between mistuning misattributions to a minor triad and instrumental experience ($\rho = -.28$, $p < .001$, $N = 151$) and between mistuning misattributions to a minor triad and age ($\rho = -.31$, $p < .001$, $N = 156$). Also, in Category 1, there was a negative correlation between mistuning misattributions to a minor triad and instrumental experience ($\rho = -.31$, $p < .001$, $N = 153$) and between mistuning misattributions to a minor triad and age ($\rho = -.36$, $p < .001$, $N = 158$). In Category

2, the same correlation occurred only between misattributions to a minor triad and age ($\rho = -.16$, $p < .05$, $N = 163$). The polarity of Category 2 was perhaps seen here.

However, there was no statistically significant correlation between mistuning misattributions to a minor triad, on the other hand, and either instrumental experience or age, on the other in Category 3. By contrast, there was a strong negative correlation between mistuning misattributions to a *major triad*, on the other hand, both instrumental experience ($\rho = -.43$, $p < .001$, $N = 160$) and age ($\rho = -.51$ $p < .001$, $N = 165$), on the other hand in Category 3. The more aged and instrumentally experienced the participants were, the less misattributed modally altered major triads in Category 3.

There was a negative correlation between mistuning misattributions to a major triad and instrumental experience ($\rho = -.47$, $p < .001$, $N = 151$) and between mistuning misattributions to a major triad and age ($\rho = -.49$, $p < .001$, $N = 156$). As written in previous lines, the negative correlation was the strongest in Category 3 ($\rho = -.43$, $p < .001$, $N = 160$) between mistuning misattributions to a minor triad and instrumental experience. In relationship with age, the negative correlation was even stronger ($\rho = -.51$, $p < .001$, $N = 165$). In Category 2, the corresponding values were $\rho = -.31$ ($p < .001$, $N = 158$) with instrumental experience and $\rho = -.31$ ($p < .001$, $N = 163$) with age. In Category 1, the values were $\rho = -.37$ ($p < .001$, $N = 153$) with instrumental experience and $\rho = -.35$ ($p < .001$, $N = 158$) with age.

All significant correlations between mistuning misattributions to a major triad and instrumental experience and age were negative. Participants had learned to detect a pure major triad as a pure triad (as it is) following age and instrumental experience.

3.3.5 Recognition of mistuning, music analysis observations

The means of recognition of mistuning of single chord progressions are presented in Table 28. Chord progression 9, representing Category 2, was the most difficult one for the participants: Here, only 22.4% of listeners recognized the target. Chord progression 35 from Category 1 was the easiest one: 92.2% recognized the target.

As seen in Table 28, the four chord progressions in which the target was most reliably recognized share the feature that the target is preceded by the tonic triad. Another observation is that in these cases, the harmonic progressions preceding the target are quite traditional. The tonal clarity probably helped listeners to detect the target.

The presentation order of samples in Experiment 1 was the same for all participants. This could have created an order effect in the results, which can be considered a methodological limit. To make sure this did not happen, a Pearson correlation test was conducted. It did not show clear differences in correlations between first recognitions at the beginning of the experiment nor in correlations between first and last recognitions. Statistically significant correlations occurred in correlations across the 40 samples. Correlations between recognitions are presented in Tables 46, 47, and 48 (see Appendixes 13, 14, and 15).

As can be seen in Table 28, recognition of mistuning succeeded worst in chord progression 9 ($M = 0.22$ SD = 0.42). There are parallel octaves between the soprano voice and bass voice from the previous triad (IV^{64}) to the mistuned ii triad. In traditional four-part harmony writing, this would be considered as poor voice leading and, accidentally or not, this time the target was worst recognized. There are odd chord progressions (VI^{64}-V^{64}-IV^{64}) just before the mistuned second-degree triad). These untraditional, fuzzy chord movements may perhaps explain the poor result in recognition of mistuning.

Table 28. Recognition of mistuning, ranked according to the percentage of participants recognizing the triad out of the complete data set (40 chord progressions).

Trial number	Category / progression	1st triad	2nd triad	Location of the mistuned triad (ii)				Final triad	Recognition (%)
				1	2	3	4		
35	CAT1/6	I	vi	IV	I	ii6	iii	vi	.92
19	CAT1/7	I	I6	IV	I64	ii64	I64	V	.90
21	CAT1/10	I	V6	I	ii6	iii	V	I	.82
5	CAT1/15	V6	I	ii	I	IV	I	V	.79
20	CAT2/16	I	I6	IV	V64	IV64	ii	iii	.79
40	CAT2/14	vi	I64	IV6	V6	vi6	ii	I	.77
11	CAT3/5	I	V	III	I64	ii64	I64	V	.77
32	CAT2/10	vi	I	V6	vi	ii64	IV	I	.77
2	CAT1/9	I	vi	iii6	ii64	I	I6	V	.77
33	CAT2/6	I	iii	vi	ii64	IV	V	iii	.76
16	CAT1/3	I	iii	vi	IV	I64	ii64	I	.73
30	CAT2/4	vi	iii	ii6	IV	V	IV	I	.72
15	CAT1/1	I	IV64	I	vi	iii	ii	I	.71
26	CAT1/5	I	IV	vi	iii	ii	I	V	.68
27	CAT2/2	I	iii	ii64	IV	V	vi	iii	.64
29	CAT1/14	vi	I	ii6	iii	vi	I64	V	.64
23	CAT2/5	I	I6	IV	ii6	vi64	V	I	.63
39	CAT2/12	V	I	V6	IV64	ii64	IV	I	.61

Trial number	Category / progression	1st triad	2nd triad	Location of the mistuned triad (ii)				Final triad	Recognition (%)
				1	2	3	4		
37	CAT1/12	I	vi6	iii64	ii64	iii6	vi	IV	.61
8	CAT2/15	I	iii64	vi	V6	vi6	ii64	I	.60
34	CAT1/16	I	iii64	ii64	iii6	vi	I64	V	.60
12	CAT3/8	I	IV	VI	IV	iii6	ii64	I	.58
22	CAT1/2	I	vi	iii	V	I	ii6	iii	.58
3	CAT3/1	I	iii	ii	iii	IV	VI	I	.56
7	CAT1/8	I	V6	I	iii	ii6	iii6	vi	.54
6	CAT2/3	I	I6	ii6	vi	V	vi	iii	.54
24	CAT1/13	vi	iii	ii	I	IV	vi	iii	.49
25	CAT1/11	I	IV	I6	ii6	I64	V	I	.42
13	CAT2/1	I	I6	ii6	vi	V	IV	I	.45
28	CAT3/3	I	V6	I	ii	iii	III6	I	.40
36	CAT1/4	I	V6	I	vi	iii	ii	iii	.37
18	CAT2/11	I	iii	V64	vi6	ii	vi64	I	.31
17	CAT2/7	I	iii64	vi	ii6	vi64	V64	I	.30
14	CAT3/2	I	iii64	ii64	I64	III	v	I	.28
10	CAT2/8	IV	I6	IV	ii	IV	V	iii	.28
1	CAT3/6	I	IV	VI64	I6	ii6	iii6	vi	.27
31	CAT3/7	I	V64	I6	III	I6	ii6	iii	.26
38	CAT3/4	vi	IV	I6	ii6	I64	VI 64	I	.26
4	CAT2/9	IV	I	V6	IV64	ii	vi	iii	.24
9	CAT2/13	I	iii	vi64	V64	IV64	ii	iii	.22

In the next following chord progressions, the target was also poorly recognized. There might be some explanations. We can see an example of modally altered sixth degree triad in Fig. 22, chord progression 1, CAT3/6 ($M = 0.27$, SD = 0.45). The modally altered sixth degree triad has probably fooled many participants.
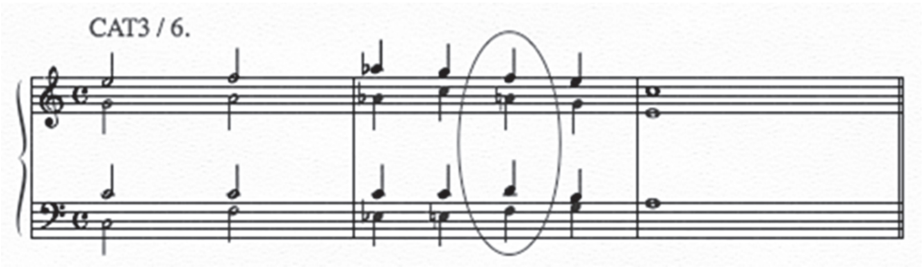
Fig. 22. Chord progression 1, CAT3/6.

In Fig. 23 we can see chord progression 4, CAT2/9 (*M* = 0.24, SD = 0.43). The untraditional harmony and the hidden tonic triad (not located in the beginning or at the end) may have made it difficult to perceive the mistuned target triad.

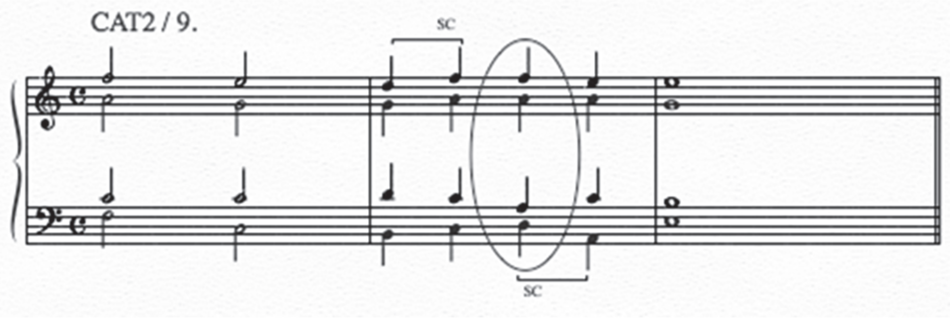

Fig. 23. Chord progression 4, CAT2/9.

Further, Fig. 24 shows us chord progression 10, CAT2/8. (*M* = 0.28, SD = 0.45). The hidden tonic triad /I6 as a second chord) may have caused confusion. It might be that, for listeners, "odd" chord progressions can complicate the recognition of mistuning.

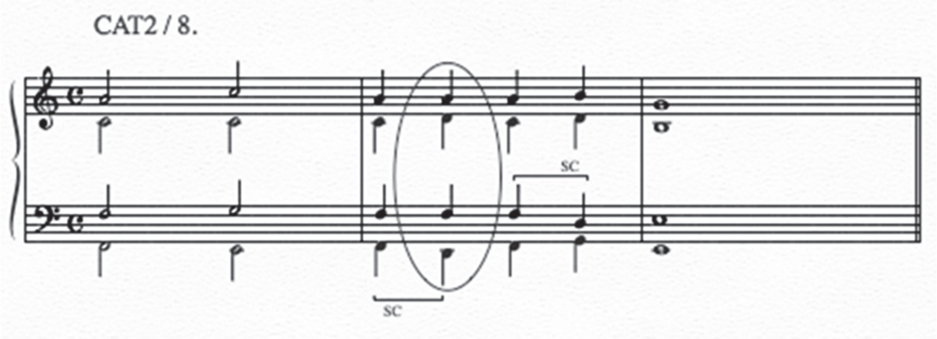

Fig. 24. Chord progression 10, CAT2/8.

Chord progression 14, CAT3/2 (*M* = 0.28, SD = 0.45) is seen in Fig. 25. These are all fuzzy factors. Three consecutive triads, each of them as a second inversion, leading to the modally altered third degree triad. In addition, the dominant triad is altered, too. It is perhaps no wonder the listeners had difficulties finding the mistuned target triad.
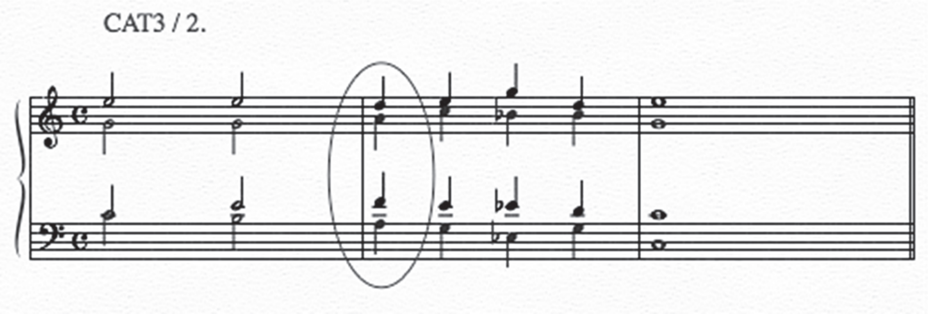
Fig. 25. Chord progression 14, CAT3/2.

Chord progression 31, CAT3/7 ($M = 0.26$, SD = 0.44) is seen in Fig. 26. The modally altered third degree triad has probably caused confusion.
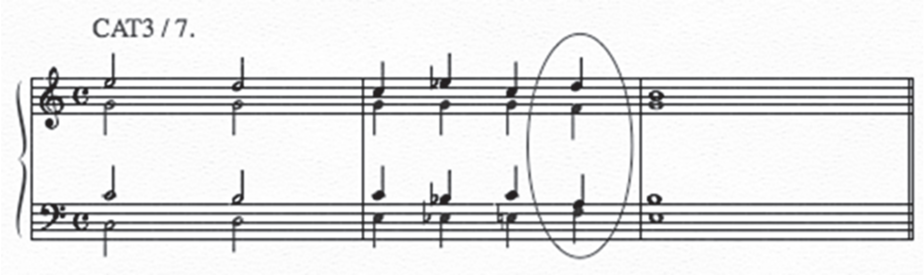
Fig. 26. Chord progressions 31, CAT3/7.

Finally, Fig. 27 presents us chord progression 38, CAT3/4 ($M = 0.26$, SD = 0.44). There are only three triads as a root version. In addition, the modally altered sixth degree triad as a second inversion has probably caused confusion.
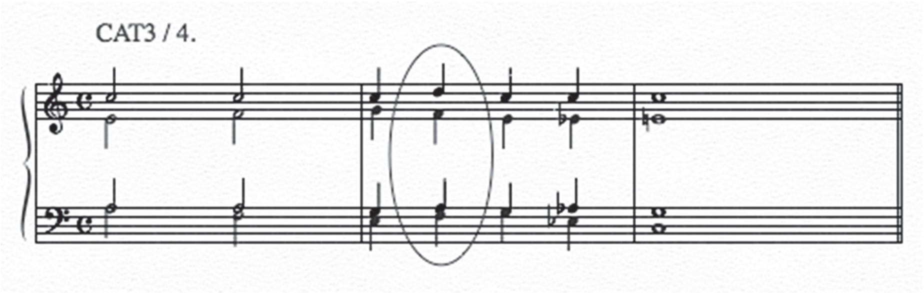
Fig. 27. Chord progression 38, CAT3/4.

As remembered from Sub-chapter 3.3.1, mistuning was detected best in A) Category 1. The set B (melodic commas) was rather close to A. In the set of chord progressions without melodic commas (C), mistuning was recognized significantly worse. The worst result occurred in Category 3 (D) which was practically equal with group C. The Category 1 is ranked according to the percentage of participants in Table 29.

Table 29. Recognition of mistuning, ranked according to the percentage of participants recognizing the target, Category 1.

Trial number	Category 1/No.	Location of the target (ii)							Recognition (%)
		1st triad	2nd triad	1	2	3	4	Final triad	
35	6	I	vi	IV	I	ii6	iii	vi	.92
19	7	I	I6	IV	I64	ii64	I64	V	.90
21	10	I	V6	I	ii6	iii	V	I	.82
5	15	V6	I	ii	I	IV	I	V	.79
2	9	I	vi	iii6	ii64	I	I6	V	.77
16	3	I	iii	vi	IV	I64	ii64	I	.73
15	1	I	IV64	I	vi	iii	ii	I	.71
26	5	I	IV	vi	iii	ii	I	V	.68
29	14	vi	I	ii6	iii	vi	I64	V	.64
37	12	I	vi6	iii64	ii64	iii6	vi	IV	.61
34	16	I	iii64	ii64	iii6	vi	I64	V	.60
22	2	I	vi	iii	V	I	ii6	III	.58
7	8	I	V6	I	iii	ii6	iii6	vi	.54
24	13	vi	iii	ii	I	IV	vi	iii	.49
25	11	I	IV	I6	ii6	I64	V	I	.42
36	4	I	V6	I	vi	iii	ii	iii	.37

A syntonic comma in melodic lines in Category 2 seemed clearly to influence the recognition of the target. In two of them (CAT2/8. and CAT2/9). there were two melodic commas. In both samples another of these melodic commas is related to the chord changes to the target triad. These two commas did not seem to help participants to recognize the target as can been seen in the following table. In Samples 5 and 12 had melodic comma in the chord change of the target triad, too, but these matters did not seem to affect the recognition of the target. The location of the melodic comma did not seem to be an essential factor in recognition of the target. The results of Category 2 are introduced ranked according to the percentage of participants in Table 30.

Table 30. Recognition of mistuning, ranked according to the percentage of participants recognizing the target, Category 2.

Trial number	Category 2/No.	1st triad	2nd triad	Location of the target (ii)				Final triad	Recognition (%)
20	16	I	I6	IV	V64	IV64	ii	iii	.79
40	14	vi	I64	IV6	V6	vi6	ii	I	.77
32	10	vi	I	V6	vi	ii64	IV	I	.77
33	6	I	iii	vi	ii64	IV	V	iii	.76
30	4	vi	iii	ii6	IV	V	IV	I	.72
27	2	I	iii	ii64	IV	V	vi	iii	.64
23	5	I	I6	IV	ii6	vi64	V	I	.63
39	12	V	I	V6	IV64	ii64	IV	I	.61
8	15	I	iii64	vi	V6	vi6	ii64	I	.60
6	3	I	I6	ii6	vi	V	vi	iii	.54
13	1	I	I6	ii6	vi	V	IV	I	.45
18	11	I	iii	V64	vi6	ii	vi64	I	.31
17	7	I	iii64	vi	ii6	vi64	V64	I	.30
10	8	IV	I6	IV	ii	IV	V	iii	.28
4	9	IV	I	V6	IV64	ii	vi	iii	.24
9	13	I	iii	vi64	V64	IV64	ii	iii	.22

The results of Category 3 are introduced ranked according to the percentage of participants in Table 31.

Table 31. Recognition of mistuning ranked according to the percentage of participants recognizing the target, Category 3.

Trial number	Category 3 / No.	1st triad	2nd triad	Location of the target (ii)				Final triad	Recognition (%)
11	5	I	V	III	I64	ii64	I64	V	.77
12	8	I	IV	VI	IV	iii6	ii64	I	.58
3	1	I	III	ii	III	IV	vi	I	.56
28	3	I	V6	I	ii	iii	III6	I	.40
14	2	I	iii64	ii64	I64	III	v	I	.28
1	6	I	IV	VI64	I6	ii6	iii6	vi	.27
31	7	I	V64	I6	III	I6	ii6	iii	.26
38	4	vi	IV	I6	ii6	I64	VI 64	I	.26

3.4 Reliability and validity

In the following sub-chapters introduce us, how the reliability and validity of Experiment were tested and reported. The validity of Experiment I is reported in Sub-chapter 3.4.1. The reliability of Experiment 1 is reported in Sub-chapter 3.4.2.

3.4.1 Validity of Experiment 1

The recognition results of the experiment were also subjected to factor analysis. We used a tetrachoric correlation matrix as a starting point for the analysis. Extraction method was Maximum likelihood, rotation method used was varimax (see Table 49 in Appendix 16 for detailed results of the analysis). The idea was to examine whether there are certain factors influencing the pitch discrimination skill of the participants in certain chord progressions and whether there is any relationship between factors and preordained categories. The chord progressions used in the present study are organized at basis of practical music theory. The mistuning to be recognized has not been chosen on the grounds of cognitive neuroscience (e.g., Slater et al., 2018) and it is not assumed that this target triad used in the present experiment would represent accurately a certain feature of voice processing functions of human brain. The results of the factor analysis of the experiment items representing factors as variables are presented in Appendix 16.

All experiment items (with somewhat sufficient loadings) from Category 1 had high loadings on Factor 1. Each of them had the tonic triad or iii triad surrounding the target. In fact, all combinations with these chords were introduced in these four chord progressions which got the highest loadings:

- iii – ii – I
- I – ii – I
- I – ii – iii
- iii – ii – iii

These kind of chord progressions is the basis of Category 1 and the experiment items representing Factor 1 originates from Category 1. The results of this factor analysis are gathered in Table 32:

- Trial 26: The previous triad before the target is the iii triad.
- Trial 5: The previous triad before the target is the tonic triad.
- Trials 35, and 36: The next triad after to the target is the iii triad.

Table 32. Experiment items representing Factor 1, by factor analysis (rotated factor matrix), maximum likelihood.

Trial number	Category	No.	Triads							Factor loading
26	CAT1	5	I	IV	vi	iii	ii	I	V	.69
5	CAT1	15	V6	I	ii	I	IV	I	V	.50
35	CAT1	6	I	vi	IV	I	ii6	iii	vi	.46
36	CAT1	4	I	V6	I	vi	iii	ii	iii	.39

Interestingly, all experiment items with highest loadings in Factor 2 belonged to Category 3. The basis of Category 3 was to examine, how pure major triads, modally altered, influences the participant’s ability to detect the target. The experiment items representing Factor 2 originates from Category 3. The results of this factor analysis are gathered in Table 33:

- Trials 3, 14: The triad right before the target is the modally altered third degree triad (III triad)
- Trials 28, 3: The next triad after to the target is the modally altered third degree triad (III triad)
- Trials 14 and 38: The next triad after the target is the tonic triad.

Table 33. Experiment items for Factor 2, by factor analysis (rotated factor matrix).

Trial number	Category	No.	Triads							Factor loading
28	CAT3	3	I	V6	I	ii	III	iii6	I	.70
14	CAT3	2	I	III64	ii64	I64	iii	v	I	.54
3	CAT3	1	I	III	ii	III	IV	vi	I	.47
38	CAT3	4	vi	IV	I6	ii6	I64	VI 64	I	.46

The loadings of experiment items in Factor 3 were originated both from Category 2 and 1. The results of factor analysis by Factor 3 are gathered to the following Table 34:

- Trials 6, 22, and 16: The triad right before the target is the tonic triad.
- Trial 2: The triad right before the target is the iii triad.
- Trials 2 and 16: The next triad after the target is the tonic triad.

Table 34. Experiment items for Factor 3, by factor analysis (rotated factor matrix).

Trial number	Category	No.	Triads							Factor loading
6	CAT2	3	I	I6	ii6	vi	V	vi	iii	.49
22	CAT1	2	I	vi	iii	V	I	ii6	iii	.44
2	CAT1	9	I	vi	iii6	ii64	I	I6	V	.38
16	CAT1	3	I	iii	vi	IV	I64	ii64	I	.38

The only chord progression from Category 2 is Trial 6 (CAT2/3). It does not include melodic commas like 10 chord progressions in Category 2. The findings of factor analysis point to the direction that the basis of the Category 1 and the Category 3 were purposefully designed.

Experiment items of Factor 1 (Category 1) and Factor 2 (Category 3) and even of Factor 3 (Category 2 and 1) included the same chord changes surrounding the target: The tonic triad and the iii triad. The only exception was Trial 6 (CAT2/3) in Factor 3: the next triad after the target was the vi triad.

The sum variable representing experiment items of Factor 1 was not normally distributed [K–S(159) = .23, $p < .001$] and [S–W(159) = .86 $p < .001$] and the distribution was clearly skewed to left (skewness = −.66, C.R. = −3.46) which differs significantly from 0 (C.R. < −1.96). Kurtosis was negative (−.45, C.R. = −1.19).

The sum variable representing experiment items of Factor 2 was not normally distributed, either [K–S(159) = .20, $p < .001$] and [S–W(159) = .86 $p < .001$] and the distribution was clearly skewed to right (skewness = .40, C.R. = 2.29) which differs significantly from 0 (C.R. > 1.96). Kurtosis was strongly negative (−1.16, C.R. = 3.02) which also differs significantly from 0 (C.R. > 1.96).

The sum variable representing experiment items of Factor 3 was non-normally distributed, too [K–S(159) = .20, $p < .001$] and [S–W(159) = .89 $p < .001$] and the distribution was perceptibly skewed to left (skewness = −.42, C.R. = −2.21) which differs significantly from 0 (C.R. < −1.96). Kurtosis was notably negative (− .67, C.R. = 1.77).

Recognition of mistuning by background variables (Factors 1, 2, and 3 as dependent variables)

Because of both normal and non-normal distributions, the multidimensional analysis was carried out both with one-way ANOVA and nonparametric Kruskal–Wallis test.

According to ANOVA, there were no statistically significant differences between instrument groups concerning Factor 1 and Factor 2. Kruskal–Wallis test confirmed these results. Instead, Factor 3 as a dependent variable, there were statistically significant differences between string instrument players and brass instrument players according to ANOVA [$F(3, 157) = 3.06$, .01, $p < .05$]. Kruskal–Wallis test did not show multiple comparison because the overall test did not show significant differences across samples. Hence, it cannot be claimed reliably that there were differences between instrument groups.

The result mentioned in previous lines differs slightly from the results of the whole data set (40 chord progressions) and its three categories: As mentioned earlier, ANOVA and Kruskal–Wallis test showed no significant differences between how well participants representing different instrument groups succeeded in recognizing the target. As remembered, the situation was the same separately for each of the stimulus Categories 1–3 (for all, $p > .05$).

According to ANOVA, there were no statistically significant differences between choir voices when there were Factors 1, 2, and 3 as dependent variables. Kruskal–Wallis test confirmed this result (for all, $p > .05$).

When compared to the findings of the whole data set (with ANOVA), same results were found: no statistically significant differences between choir voices in recognition of mistuning nor in Category 1 and in Category 3, either. These results were confirmed also by Kruskal–Wallis test (for all, $p > .05$). As remembered, there was, however, a statistically significant difference between choir voices in recognition of mistuning (ANOVA) in Category 2 [$F(2, 157) = 4.85$, $p < .01$]. Kruskal–Wallis test also showed this same difference ($p < .05$). Further analyses revealed the significant difference between top voice group and bass voice group ($z = -2.70$, $p < .01$). However, Category 2 did not stand out in factors in terms of choir voices.

What it comes to gender, the analysis was carried out both independent samples *t* test and the nonparametric Mann–Whitney U test because of both normal and non-normal distributions in male and female distributions. According to independent samples t test, there were no statistically significant differences between male and female participants in recognition of mistuning when Factors 1, 2, and 3 were set as dependent variables (for all, $p > .05$). This result was confirmed by Mann–Whitney U Test (for all, $p > .05$).

Recognition of mistuning by Factors 1, 2, and 3 (instrumental experience and age as independent variables)

As remembered, the goal in this sub-chapter, is still to estimate the validity of Experiment 1. We saw that certain factors influenced the pitch discrimination skill of the participants in certain chord progressions and the relationship between factors and preordained categories was seen. Let us continue with regression analysis. *Instrumental experience* variable and *age* variable are suitable variables for regression analysis. A scanty majority of distributions of Factors 1, 2, and 3 by instrumental experience and age were non-normally distributed. Because of this, the results are acceptable with certain reservations. It is possible that all connections between variables did not appear in these analyses. *Factor 1* variable was set as a dependent variable. *Instrumental experience* variable and *age* variable were set as independent variables.

A simple linear regression was calculated to predict participants' recognition of mistuning (Factor 1) based on instrumental experience and age. Instrumental experience and age together explained 12.7% of recognition of mistuning (Factor 1) which can be regarded as perceptible [$F(2, 155) = 11.29$, $p < .001$]. When age increased by one year, recognition of mistuning (Factor 1) increased by 0.07 unit element ($p < .05$). The connection between recognition of mistuning and instrumental experience was not statistically significant in Factor 1 ($p > .05$). Put in formula:

$$\text{Recognition of mistuning} = 1.626 + 0.065 \times \text{age} + 0.041 \times \text{instrumental experience}$$

$$\text{Recognition of mistuning} = \text{Recognition of mistuning in Factor 1}$$

A simple linear regression was calculated to predict participants' recognition of mistuning (Factor 2) based on instrumental experience and age. Instrumental experience and age together explained 25.1% of recognition of mistuning (Factor 2) which can be regarded as notable [$F(2, 157) = 26.34$, $p < .001$]. When age increased by one year, recognition of mistuning (Factor 2) increased by 0.13 unit element ($p < .001$). The connection between recognition of mistuning and instrumental experience was not statistically significant in Factor 2 ($p > .05$). Put in formula:

Recognition of mistuning = −.65 + 0.133 × age + 0.054 × instrumental experience

Recognition of mistuning = Recognition of mistuning in Factor 2

A simple linear regression was calculated to predict participants' recognition of mistuning (Factor 3) based on instrumental experience and age. Instrumental experience and age together explained 4.1% of recognition of mistuning (Factor 3) which can be regarded as modest [$F(2, 154) = 3.32$, $p < .05$]. The connection between recognition of mistuning (Factor 3) and instrumental experience nor with age were not statistically significant in Factor 3 (both $p > .05$). Put in formula:

Recognition of mistuning = 2.075 + 0.021 × age + 0.040 × instrumental experience

Recognition of mistuning = Recognition of mistuning in Factor 3

3.4.2 Reliability of Experiment 1

The value of Cronbach's α is a common key ratio to measure the reliability of the study. It is known as a split-half test which gives an average correlation of all possible split halves. Cronbach's α is an estimate of this. If this value is for instance 0.9, it means that 90% of the variability in the observation is true and 10% is due to error (Roberts, Priest & Traynor, 2006, p. 42). The value of Cronbach's α should be 0.7 or more in reliable studies (Cortina, 1993, p. 101).

Recognition of mistuning in the whole data set (40 chord progressions)

The inner validity of the sum variable *recognition of mistuning* (the whole data set, 40 chord progressions) seems quite good (Cronbach's α = .785). When viewing the separate chord progressions, it can be seen that the values of Cronbach's α were sufficient. However, there were some chord progressions, which lower the reliability:

- Trial 39: CAT2/12.
- Trial 37: CAT1/12.
- Trial 32: CAT2/10.
- Trial 8: CAT2/15.
- Trial 18: CAT2/11.

- Trial 12: CAT3/8.

If any of these six chord progressions were deleted from the data set, the value of Cronbach's α would rise from the value (Cronbach's α = .785). Regarding Category 1 of recognition of mistuning, the value of the Cronbach's α (.65) was still sufficient. In Category 2 of recognition of mistuning, the value of the Cronbach's α (.44) was not sufficient. The two clear dimensions of this category (a syntonic comma in melodic movements—no melodic commas) probably weakens the inner validity. Concerning Category 3 of recognition of mistuning, the value of the Cronbach's α (.64) was still sufficient. Regarding melodic commas from Category 2 the value of Cronbach's α (.48) did not rise a lot from the value of Category 2.

Mistuning misattributions to a minor triad and major triad (data set: 29 experiment items)

Misattributions to a minor triad did not achieve a sufficient value of Cronbach's α (.36). The three categories of misattributions to a minor triad got even worse values. These three categories were not used in reporting results of the experiment. Instead, misattributions to a major triad achieved a satisfying value of Cronbach's α (.708). The three categories of misattributions to a major triad got scantily lower values (Cronbach's α < .6).

The results of the experiment were reported so that misattributions to a minor and major triad as frequency distributions were reported in the data set of 29 experiment items but not in separate categories. In the same way, they were used as dependent variables in multidimensional analysis.

The values of Cronbach's α (Location 1 = .67, Location 2 = .50, Location 3 = .07, Location 4 = .48) in four different locations of the target differed a lot from each other. The locations were not used as dependent variables in multidimensional analysis. The distributions of the recognition of mistuning by locations and their differences were reported.

The experiments items representing Factor 1 (.598), Factor 2 (.736) achieved a sufficient value of Cronbach's α. The experiment items representing Factor 3 (Cronbach's α = .444) was clearly weaker. The distributions of experiment items for Factors 1, 2, and 3 were reported and they were used as dependent variables in multidimensional analysis.

Cronbach's α measures the reliability best when variables are one-dimensional. Factor analysis in the previous sub-chapter pointed that the variables which measures the recognition of mistuning of a syntonic comma are multidimensional. Therefore, the values of Cronbach's α might be underestimated.

The content validity and the criterion validity

The content validity of this experiment can be examined from the viewpoint of the recognition of the target. It could be argued that the recognition of the mistuned triad (manipulated by certain idea) measures only the reaction to mistuned triad itself. Indeed, the recognition of the syntonic comma alone is not a music psychological property. However, this sensitivity to perceive this kind of mistuning relates to pitch discrimination skills. The mistuned minor triad narrowed by a syntonic comma both from the part of third and fifth, is suitable representative and traditionally judged as unusable. Musicians and music amateurs must notice certain kind of mistunings to be able to play and sing successfully. The criterion validity of this experiment cannot be estimated because, because there should be an alternative test which could be used as testing the recognition of mistuning by a syntonic comma.

4 Experiment 2: Intonation preferences

The fourth main chapter introduces the second experiment of this research, the experiment of intonation preferences (Experiment 2). The aims are revised in Sub-chapter 4.1. The method of experiment is presented in Sub-chapter 4.2. The results of this experiment are reported in Sub-chapter 4.3. Finally, Sub-chapter 4.4 includes the operations of reliability and validity.

4.1 Aims of Experiment 2

The purpose of experiment of intonation preferences was to clarify which strategies of tuning alternatives for solving the dilemma of the syntonic comma would be most preferred by listeners. In particular, it was hoped that the experiment would shed light on listeners' sensitivity to the tuning strategy of pitch drift as a means of eliminating the syntonic comma in a tonal homophonic context. In order to set pitch drift in context, the experiment was designed to also include three other important tuning strategies, all differing in their basic orientation. It could be assumed that various contextual criteria greatly affect the preferences of the differences of tuning alternatives that are due to different comma placements. In summary, the following four tuning strategies were used in the experiment:

- *Pitch drift*: The triad that would otherwise involve the syntonic comma (the second-degree minor triad) is not tempered, but performed vertically pure in just intonation. This operation causes the pitch drift by a syntonic comma, either upward or downward. Melodic syntonic commas linked to the second-degree minor triad are also inevitable. This is a local usage of the syntonic comma.
- *Local tempering*: The syntonic comma triad (the second-degree minor triad) is tempered in equal temperament whereas other triads remain pure. This is a local usage of syntonic comma.
- *Equal temperament*: This is a global usage of the problem of the syntonic comma.
- *Meantone tuning*: This is a global usage of the problem of the syntonic comma.

4.2 Method of Experiment 2

This sub-chapter is divided on five sub-chapters. Sub-chapter 4.2.1 includes the essential information of the participants of Experiment 1. Musical material is described in Sub-chapter 4.2.2 and it is an overview of self-made chord progressions and tuning manipulations used in this experiment. Sub-chapter 4.2.3 introduces the design of this experiment. Procedure is presented in Sub-chapter 4.2.4 and data analysis in Sub-chapter 4.2.5.

4.2.1 Participants

The participants were 93 (70 females, 23 males) students of music education and musicology at the Universities of Oulu and Jyväskylä in Finland, as well as professional music teachers in primary schools, upper primary schools, and secondary schools in Finland. Professional teachers had a previous degree in music education from a university or a music academy. Their ages ranged between 19 and 60 years, the *M* age being 28.12 years (SD = 10.09).

The participants reported a wide range of previous musical experience. The duration of playing the main instrument ranged between 5 and 50 years, with a *M* of 18.42 (SD = 10.47). In the beginning of the research it was assumed that especially university music students would have a broad spectrum of main instruments. Therefore, the division to string instruments, brass instruments, woodwind instruments and other instruments seemed a reasonable starting point Sfor constructing a background variable for the questionnaire. However, it turned out that there were only a few orchestral instrument players, and instead, 68 of the participants (73.1%) reported their main instrument as belonging to the fourth category: piano, kantele, guitar, harp, percussion. In addition, there were 15 string instrument players (16.1%), but only two brass players (2.2%) and seven woodwind instrumentalists (7.5%; one participant did not report a main instrument). Due to the uneven distribution, the participants' main instrument cannot be treated as an independent variable in the analysis of the results below. In hindsight, it would have been wise simply to ask about the main instrument with an open question.

Concerning the participants' main musical learning environment, the prior assumption was that the individuals could be suitably divided in three groups, given as alternatives in the questionnaire. According to this scheme, 52 (55.9%) of the participants reported their *main* musical experience to be from a classically oriented institute, while 25 participants reported a background in the music programs of primary or secondary schools with music orientation (26.9%), and 16 reported a background in popular music bands (17.2%). They were asked to name one musical background that they experienced as dominant. The participants were given a possibility to clarify their chosen alternative, and several of them did. However, it turned out to be quite difficult to use the open answers for further specifying of the categories.

According to given alternatives and open answers, the only clear-cut binary distinction in terms of musical background that runs across the whole group of participants was whether or not they had prior experience in choral singing. In this respect, the questionnaire revealed two groups: participants who had experience in choral singing before professional studies (51; 54.8%) and participants, who were lacking in such experience (42; 45.2%).

In the next Sub-chapter 4.2.2, I will introduce a sheet music example of every tuning alternatives of Experiment 2. All pitch drift samples are introduced in Appendix 8.

4.2.2 Musical materials

To clear these four tuning manipulations, we take a short overview to them. First, I introduce the example of an example of pitch drift. Pitch drift happens downward in an example in Fig. 28. A sheet music example of local tempering is presented in Fig. 29.

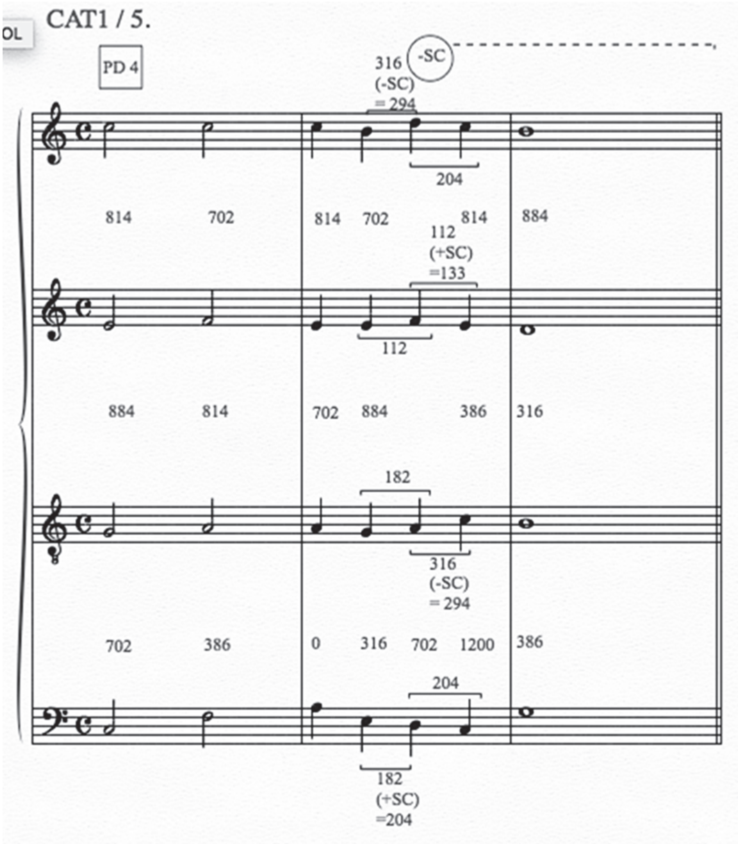

Fig. 28. A sheet music example of pitch drift.

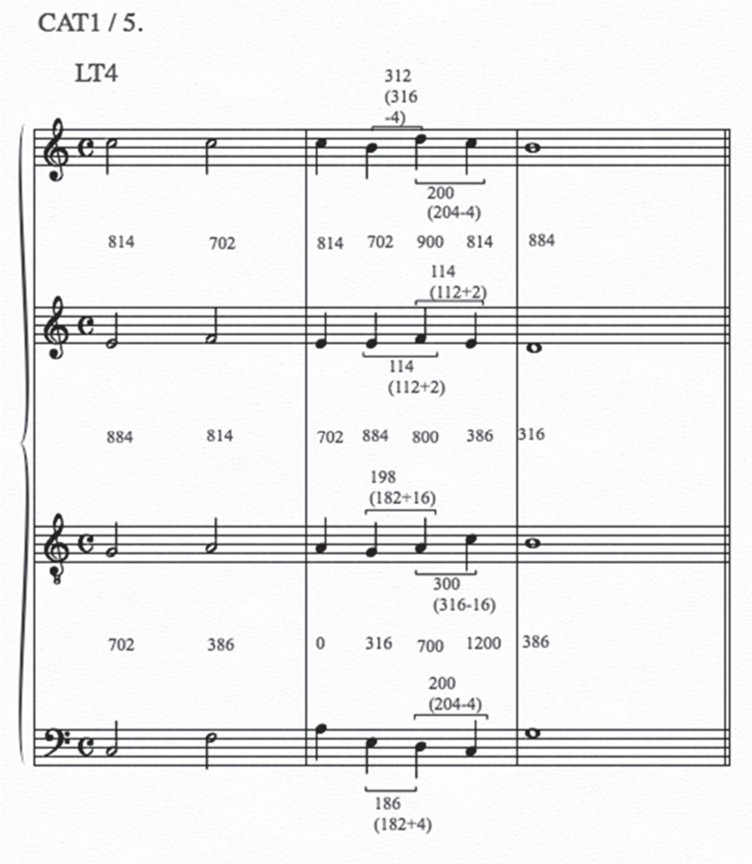

Fig. 29. A sheet music example of local tempering.

Equal temperament was presented in Sub-chapter 2.1.6. As remembered, all the sizes (in cents) of intervals vertically and horizontally are divisible by 100. The local tempering manipulation uses the just intonation scale presented earlier. The only exception is the second-degree minor triad, which is tuned into equal temperament. This means, of course that some melodic movements are not from just intonation scale nor from equal temperament. The modified just intonation scale extended by local tempering is presented in Table 35.

Table 35. Intervals of the modified just intonation scale (2015) extended by local tempering.

Intervals	1	m2	M2	m3	M3	4	#4	5	m6	M6	m6	M7
Cents		70.67		315.64			590.22		813.69		1017.60	
Solfeggio		di		ma			fi		lo		ta	
Cents	0		203.91		386.31	498.04		701.96		884.36		1088.27
Solfeggio	do		re		mi	fa		so		la		ti
Cents in equal temperament			200 in ii triad			500 in ii triad				900 in ii triad		

Meantone tuning used in this experiment was well-known ¼ comma meantone tuning from Pietro Aaron (1523). A sheet music example of it is presented in Fig. 30.
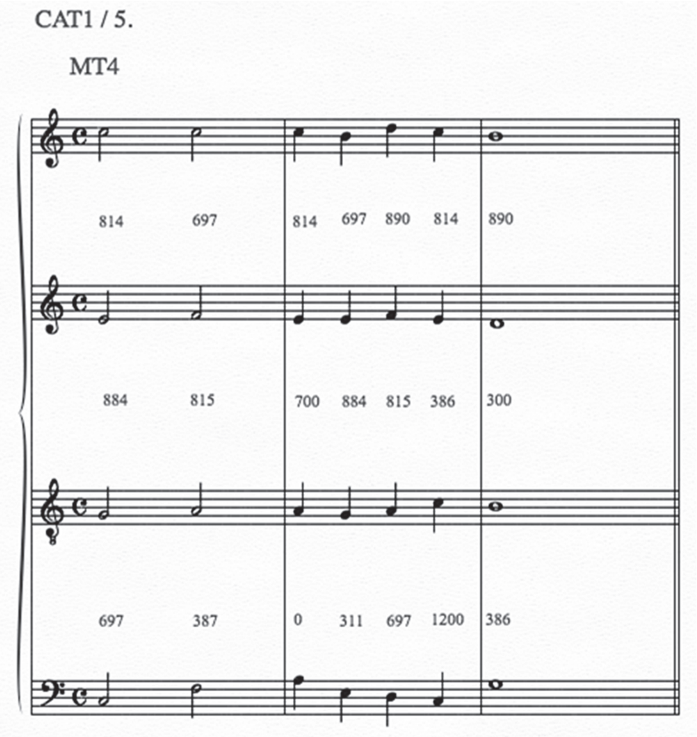
Fig. 30. A sheet music example of meantone tuning.

The 30 chord progressions for this second experiment were selected from the score of mistuning recognition. These chord progressions were selected so that their harmony would work with all these four tuning alternatives. The solution was simply omitting the chord progressions of Category 3 because of modally altered triads of the third degree and the sixth degree. The musical material was thereby homogenized. The most challenging manipulation was pitch drift. The harmonies of chord progressions had to produce a possibility to the raise or lower fundamental frequency: There were found 20 chord progressions of total 40, which included a possibility to pitch drift. Finally, 15 chord progressions were selected for comparisons of pitch drift preferences with all other alternatives. After this, categories lost their significance. They only had to work with these four tuning alternatives.

The minimum number of samples was 15 (5 × 3 comparisons) for each tuning choice; therefore, the most suitable 15 samples from 20 possibilities for pitch drift were selected:

- Pitch drift-local tempering (five chord progressions)
- Pitch drift-equal temperament (another five different chord progressions)
- Pitch drift-meantone tuning (another five different chord progressions)

In comparisons of local tempering-equal temperament and local tempering-meantone tuning and equal temperament-meantone tuning, there were no such limits (those of pitch drift). So, I added five separate chord progressions more to local tempering-equal temperament. Then I added five separate chord progressions more to local tempering-meantone tuning and finally, five separate chord progressions more to equal temperament-meantone tuning. As a result, there were 30 chord progressions to be used. Every chord progression was used in one experiment trial. The six comparisons were performed five times. The keys were picked up directly from the keys of selected chord progressions of mistuning recognition. When the order of comparison pairs was fixated, the keys of three chord progressions were change, all because of pitch drift settings. The variety of keys is practically random. The order of the experiment trials was selected according to the Table 36.

Every chord progression was presented twice in one trial, always with two separate tuning alternatives. The experiment was designed with a view to presenting all of the possible pairwise comparisons between four tuning strategies (pitch drift, local tempering, equal temperament, meantone tuning). Each consecutive block of six trials in the experiment covered all of the possible six pairs of tuning alternatives. As seen in Table 36, each consecutive block involved the same order of six pairwise comparisons, with the temporal order of the alternatives within the trials switched between consecutive blocks. So, each tuning manipulation was performed through 15 chord progressions. The full score of the experiment is seen in Appendix 7. Each pair with tuning alternatives was performed five times, always with a different chord progression.

The keys of chord progressions in 30 test trials were randomly organized into 10 keys: C (five trials) D (two trials), Eb (three trials), E (three trials), F (two trials), Gb (four trials), G (two trials), Ab (four trials), A (three trials), and Bb (two trials). The keys inherited mostly (27/30) from the trials of experiment of mistuning recognition. The procedure of key selection in that experiment is reported in Sub-chapter 3.2.2. The key of three trials had to be altered because of practical reasons. The order of the tuning alternatives was:

- Pitch drift
- Local tempering
- Equal temperament
- Meantone tuning

The presentation order of the tuning alternatives is shown in Table 36. The order of the comparisons was the same in trials 1–6, 13–18, and 25–30. The order reversed in trials 7–12 and 19–24 (pitch drift-local tempering to local tempering-pitch drift). The order and the selection of the keys were randomized. The intention was that the trials were performed in several keys to avoid fatiguing to one key.

Table 36. Experiment on intonation preferences: Final order of comparison pairs, categories of chord progressions, and key.

Sample	a)	b)	Category	Key
1	LT[1]	PD[2]	CAT1/1	C
2	ET[3]	MT[4]	CAT1/16	A
3	PD	ET	CAT1/9	Bb
4	LT	MT	CAT1/ 4	A
5	ET	LT	CAT2/16	Eb
6	PD	MT	CAT2/5	E
7	PD	LT	CAT1/2	Eb
8	MT	ET	CAT2/1	D
9	ET	PD	CAT1/10	D
10	MT	LT	CAT1/7	E
11	LT	ET	CAT3/5	C
12	MT	PD	CAT2/7	F
13	LT	PD	CAT1/3	Gb
14	ET	MT	CAT2/3	Eb
15	PD	ET	CAT1/13	Gb
16	LT	MT	CAT1/8	C
17	ET	LT	CAT3/2	Gb
18	PD	MT	CAT2/9	Gb
19	PD	LT	CAT1/5	C
20	MT	ET	CAT2/4	A
21	ET	PD	CAT1/14	C
22	MT	LT	CAT1/11	Ab
23	LT	ET	CAT3/7	F
24	MT	PD	CAT2/11	G
25	LT	PD	CAT1/6	Ab
26	ET	MT	CAT2/6	Ab
27	PD	ET	CAT2/2	Bb
28	LT	MT	CAT1/12	E
29	ET	LT	CAT3/3	G
30	PD	MT	CAT2/13	Ab

[1] LT = local tempering, [2] PD = pitch drift, [3] ET = equal temperament, [4] MT = meantone tuning

The chord progressions were notated with Finale software (2012), converted to MIDI files and transferred into Pro Tools software. All samples and their tuning systems were manipulated with Pro Tools. The final samples were produced with the basic piano sound from the Korg M1 synthesizer.

4.2.3 Design

Participants' preferences for these four tuning alternatives are in focus in this experiment. For each tuning choice, the dependent variable was the frequency of choosing this manipulation in the set of paired comparison trials involving this particular manipulation as one of the two alternatives. Besides the relative preference for the various tuning alternatives, an important goal was to explore whether and how different musical backgrounds would affect participants' sensitivity to how they prefer these alternatives. Besides age and gender, other independent variables were chosen to reflect various aspects of the participants' musical background: instrument group and years of playing the main instrument.

4.2.4 Procedure

The participants were tested in small groups, with each of them wearing headphones. There were 11 sets of similar headphones available (Shure SRH 440), and thus a maximum of 11 participants could complete the experiment at the same time. The number of participants running the experiment varied depending on circumstances. The stimuli were played back on a CD player (Sony CDP-212, with Behringer Powerplay Pro-XL, 4-channel High-Power Headphones Mixing and Distribution Amplifier, Model HA 4700). The volume was adjusted to a comfortable listening level, keeping it exactly on the same level for all participant groups. Given the measures taken, the division of the participants into small groups will have no practical significance for the research, and the participants may thus in the following be treated as one larger group. The circumstances remained the same across groups.

In the beginning of the session, the participants were informed of details. Then they were asked to sign an informed consent form and filled out a questionnaire of background information on the front page of the response packet (see Appendix 4). After this, they received spoken instructions for the test. The content of these instructions was also summarized in the response packet. When the experiment began from the CD, the instructions were repeated on the headphones, followed by one practice trial.

After this, in each of the 30 trials (60 sample chord progressions), the participants' task was to listen to the two versions of a chord progression (both involving a different tuning manipulation of the same chord progression), and indicate which one of them they preferred. The chord progression duration was 12 seconds including a rest of equal duration between the items of comparison. After each trial, there was a pause of 7–8 seconds. during which the number of the next trial was heard spoken. The trial duration was approximately 35 seconds and the whole listening task thus took 18 minutes. The total duration of the experimental sessions was 25 minutes, at a maximum.

4.2.5 Data analysis

The basis of statistical data processing in confidence interval for *M* was ($p = .05$, CI = 95%). However, there were comparisons of several sum variables. Because of this, Bonferroni corrections were calculated so that CI was 99.5% for four variables resulting in 95% confidence level for overall comparisons. Relative preferences for tuning alternatives in pairwise comparison were analyzed using Chi-square test (with Yates's continuity correction).

Most of the multidimensional analyses with background variables were done both with parametric and nonparametric tests, because the frequency distributions were not normally distributed. The one-way ANOVA (with Bonferroni post hoc test, when necessary) test was used with *instrument group* variable and *choir voice* variable. Also, Kruskal–Wallis tests were used with the *instrument group* variable and the *choir voice* variable: Pairwise comparisons were done using the Dunn test.

The analyses concerning the *gender* variable were done using independent samples t test and in addition, nonparametric Mann–Whitney U test. Correlations between dependent variables, on the other hand, and *instrumental experience* variable and *age* variables, on the other, were done by nonparametric Spearman's ρ because of non-normal distributions. For repeated measures, we used Friedman's ANOVA along with the Dunn–Bonferroni post hoc test for dependent samples.

The validity of the experiment was tested by PCA. As all the variables corresponding to the test items were binary, we used tetrachoric correlation matrix as a starting point for PCA. The tetrachoric correlation is, essentially, an estimate of the product–moment correlation that would have been obtained with the underlying continuous variables if their joint distribution was bivariate normal (see Lorenzo-Seva & Ferrando, 2012). Rotation method was varimax and by factor analysis rotated factor matrix. For reliability, Cronbach's α were determined for sum variables created basing on the results of factor analysis.

4.3 Results

The results of this experiment are presented in four sub-chapters. Preferences of the four tuning alternatives are reported in Sub-chapter 4.3.1. Comparisons of those same alternatives are reported in Sub-chapter 4.3.2. The influence of background variables is presented in Sub-chapter 4.3.3. Finally, Sub-chapter 4.3.4 includes the comparisons of preferences between experiment blocks.

4.3.1 Preferences of the four tuning alternatives

The following sub-chapters includes the results of the four tuning alternatives. Pitch drift preferences, local tempering preferences, equal temperament preferences, and meantone tuning preferences are reported each of them in separate graphics.

Pitch drift preferences

A single participant could theoretically prefer a single tuning manipulation at most 15 times. For pitch drift, the range of preference judgments ranged between 0 and 10 ($M = 3.48$, median = 3, SD = 2.22, $N = 92$). In general, most of the participants appeared to have disliked the sound of pitch drift, in comparison to the alternatives presented. As can be seen in Fig. 31, the distribution of pitch drift preferences was nevertheless significantly (C.R. > 1.96) skewed to the right (skewness = .88, C.R. = 3.50), due to a minority of participants who apparently accepted this tuning manipulation. Kurtosis was also notable (.62, C.R. = 1.24). Kolmogorov–Smirnov test [K–S(92) = .18, $p < .001$] and Shapiro–Wilk test [S–W(92) = .93, $p < .001$] both confirmed the perceived non-normality.

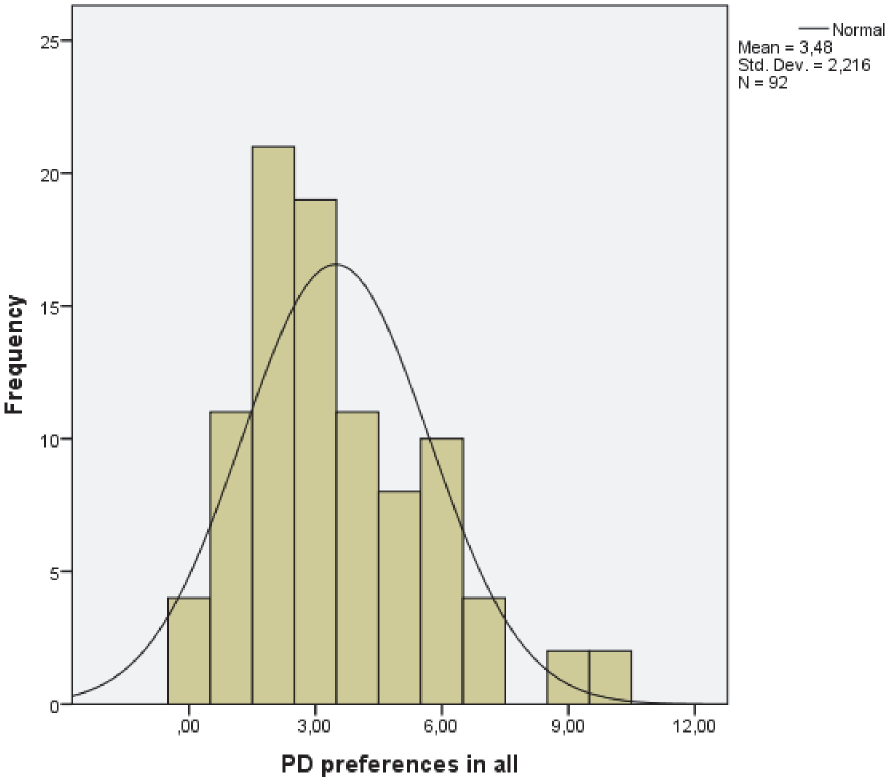

Fig. 31. The distribution of pitch drift preferences. Horizontal axis = correct responses. Vertical axis = number of participants. PD preferences = Pitch drift preferences.

Local tempering preferences

This tuning manipulation was better accepted among participants ($M = 7.92$, SD = 1.84, $N = 92$). As seen in Fig. 32, there was a concentration of observation units for frequencies 6–9. Not less than 20 participants have preferred local tempering eight times of 15 possible. The range of observation units was from 1 to 12 (median = 8). The distribution of local tempering preferences was skewed to left (skewness = −.40, C.R. = −1.61) and it was non-normal [K–S(92) = .12, $p < .01$] and [S–W(92), .94, $p < .001$]. Kurtosis was remarkable (1.38, C.R. = 2.76) which differed significantly from 0 (C.R. > 1.96).

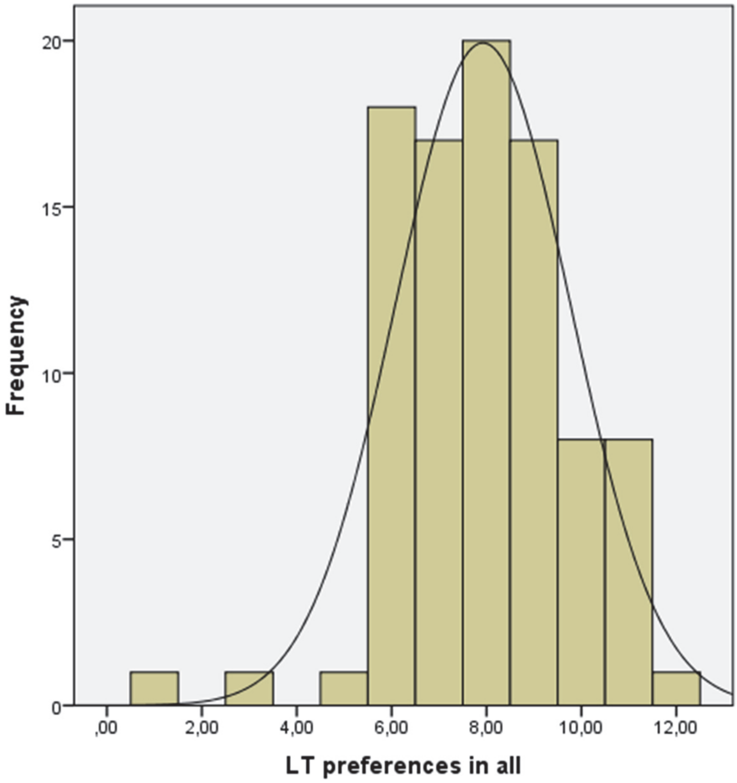

Fig. 32. The distribution of local tempering preferences. Horizontal axis = correct responses. Vertical axis = number of participants. LT preferences = Local tempering preferences.

Equal temperament preferences

Equal temperament was the most popular choice among four tuning alternatives ($M = 9.54$, SD = 2.26, $N = 92$). The range of observation units was from 5 to 15 (see Fig. 33). Median was 9 preferences (17 participants). Also 11 preferences had same frequency, 17 participants. One single participant preferred equal temperament 15 times, which is the maximum. Only three participants chose equal temperament five times. The distribution of equal temperament preferences was not normal according to Kolmogorov–Smirnov test [K–S(92) = .11, $p < .01$]. Shapiro–Wilk test, instead, [S–W(92) = .97, $p = .067$] showed roughly a normal distribution. Kurtosis of the distribution was perceptibly negative (−.051, C.R. = −1.03) and skewness (.03, C.R. = 0.11) practically neutral.

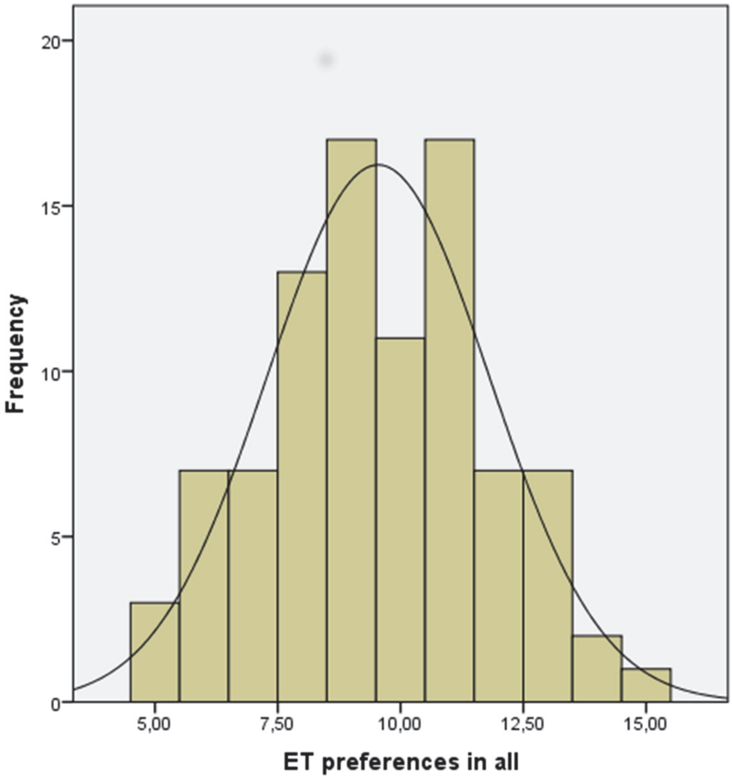

Fig. 33. The distribution of equal temperament preferences. Horizontal axis = correct responses. Vertical axis = number of participants. ET preferences = Equal temperament preferences.

Meantone tuning preferences

Meantone tuning was also well accepted by most participants in this experiment ($M = 9.05$, SD = 1.96, $N = 92$). The range of meantone tuning preferences was from 4 to 14. Median (9) was actualized with 20 participants which is the highest number in frequencies in this experiment together with local tempering preferences (20 participants having eight local tempering preferences). A total of 16 participants had 11 meantone tuning preferences, while 80.7% of participants had 7–11 meantone tuning preferences, which is a bump in distribution (see Fig. 34).

The distribution of meantone tuning preferences did not obey a normal distribution according to Kolmogorov–Smirnov test [K–S(92) = .11, $p < .01$] and Shapiro–Wilk test [S–W(92) = .97, $p < .05$]. Kurtosis was notably negative (−.34, C.R. = −.67) and the distribution was minimally skewed to left (skewness = −.08, C.R. = −.20).

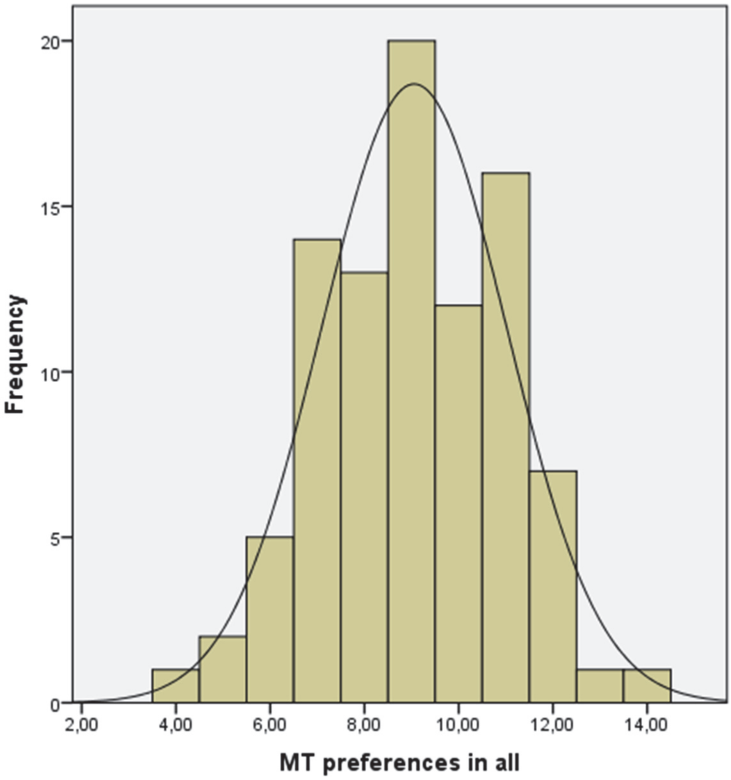

Fig. 34. The distribution of meantone tuning preferences. Horizontal axis = correct responses. Vertical axis = number of participants. MT preferences = Meantone tuning preferences.

4.3.2 Comparisons of preferences of four tuning alternatives

Theoretically speaking, if one of the four tuning alternatives would have always been found more preferable to each of the three alternatives, it would have reached 1,380 hits out of a total 2,760 hits. Equal temperament (878 preference judgments) and meantone tuning (833 preference judgments) received almost equal total scores. Not so far away from these two alternatives were local tempering (729 preference judgments). Pitch drift was least preferred with only 320 hits. These values are interlinked, or course: If one chooses one alternative, one rejects another. The differences between preferences between these four alternatives are important to clarify. The differences of intonation preferences between the four tuning alternatives in relationship with descriptive values were tested. The values are gathered to Table 37.

Table 37. Values and confidence intervals of means and medians for intonation preferences (*N* = 92).

Tuning alternative	Max 30			CI[4] = 99.2% (bootstrap) *M*		CI = 99.2% (bootstrap) Mdn		CI = 99.2% (bootstrap) SD	
	M[1]	Mdn[2]	SD[3]	lower	upper	lower	upper	lower	upper
PD[5]	3.48	3.00	2.22	2.88	4.16	2.00	4.00	1.72	2.67
LT[6]	7.92	8.00	1.84	7.41	8.42	7.00	8.50	1.43	2.29
ET[7]	9.54	9.00	2.26	8.88	10.18	9.00	10.50	1.86	2.60
MT[8]	9.05	9.00	1.96	8.49	9.63	8.00	10.00	1.61	2.29

[1] *M* = mean, [2] Mdn = median, [3] SD = standard deviation, [4] CI = confidence interval,

[5] PD = pitch drift, [6] LT = local tempering, [7] ET = equal temperament, [8] MT = meantone tuning

The confidence intervals of mean and median were not overlapping between pitch drift preferences and local tempering, equal temperament, and meantone tuning preferences. In addition, the same situation was between local tempering preferences and equal temperament preferences and also between local tempering preferences and meantone tuning preferences. It can be rather securely stated that the locations of distributions of these tuning alternatives were distinct.

Instead, the confidence intervals of mean and median among equal temperament and meantone tuning preferences were broadly overlapping, distributions were close to equal. When it comes to confidence intervals of Standard deviations, all the preferences were overlapping other preferences.

As described earlier, there were six pairwise comparisons in the experiment and they were repeated five times. Table 38 illustrates how the four tuning alternatives were preferred against each other. A series of Chi-square tests (with Yates' continuity correction) has been used to assess the extent to which the observed values represent statistically significant deviations from a theoretically even outcome—with both tuning alternatives being selected in 50% of the responses. The observation unit in this comparison is the choices made by participants.

When pitch drift was compared to equal temperament and meantone tuning, the results were quite clear: pitch drift was shunned. Local tempering-pitch drift comparisons were not equal: local tempering gathered approximately 60% from preference judgments against pitch drift. pitch drift enjoyed some relative success only in comparison to local tempering, nevertheless remaining the less favored alternative. equal temperament and meantone tuning were practically equal. equal temperament was slightly more preferred compared with local tempering. It is a bit surprising that local tempering was slightly more preferred against meantone tuning, but the result was not significant (*p* > .05).

Table 38. Relative preferences of tuning alternatives in pairwise comparison (percentages pertain to the term in the left column).

Tuning alternative	PD[1]	LT[2]	MT[3]
LT	59.8%		
	χ2 (1) = 17.22, *p* < .001		
	N = 92		
MT	85.9%	45.4%	
	χ2 (1) = 235.31, *p* < .001	χ2 (1) = 3.65, *p* > .05	
	N = 93	*N* = 93	
ET[4]	85.2%	56.1%	50.9%
	χ2 (1) = 226.8, *p* < .001	χ2 (1) = 6.58, *p* = .01	χ2 (1) = 0.11, *p* > .05
	N = 93	*N* = 93	*N* = 92

[1] PD = pitch drift, [2] LT = local tempering, [3] MT = meantone tuning, [4] ET = equal temperament

Correlations between preferences for tuning alternatives

Because of non-normal distributions of separate tuning alternatives, nonparametric Spearman's ρ was used for seeking connections between preferences: There were several correlations between preferences for the four tuning alternatives.

There was a strong, statistically significant negative correlation (ρ = −0.54) between pitch drift preferences and equal temperament preferences (*p* < .001). The more participants preferred equal temperament, the less they preferred pitch drift. This correlation was the strongest direct correlation between separate tuning preferences. All significant correlations are presented in Table 39.

Table 39. Significant correlations for intonation preferences according to nonparametric Spearman's ρ.

Variables	MT-PD ET-PD	MT-LT ET-LT	ET-MT
	PD[1]	LT[2]	MT[3]
MT	$\rho = -.30$, $p < .01$ $N = 92$	$\rho = -.36$, $p < .001$ $N = 92$	
ET[4]	$\rho = -.54$, $p < .001$ $N = 92$	$\rho = -.32$, $p < .01$ $N = 92$	$\rho = -.23$, $p < .05$ $N = 92$

[1] PD = pitch drift, [2] LT = local tempering, [3] MT = meantone tuning, [4] ET = equal temperament

The more participants preferred meantone tuning, the less they preferred pitch drift. The more participants preferred equal temperament, the less they preferred local tempering. The more participants preferred meantone tuning, the less they preferred local tempering. The more participants preferred meantone tuning the less they preferred equal temperament. The negative correlation between equal temperament and meantone tuning preferences can be interpreted as mutually exclusive two for participants.

4.3.3 Background variables

As remembered, because of the uneven distribution, the participants' main instrument could not be treated as an independent variable in the analysis of the results below. Instead, the participants' division to those who had experience in choir singing and those who lacked such experience, was clear. In the questionnaire, 51 of the 93 participants reported experience from singing in choirs. Such experience might conceivably help sensitize the students to slight differences in tuning, and hence possible differences in the tuning preferences due to the participants' choral background were examined.

The normality tests for pitch drift preferences, local tempering preferences, equal temperament preferences, and meantone tuning preferences by choir background are presented in Table 50 in Appendix 17. Because of the majority of non-normal distributions, the comparisons were carried out by nonparametric Mann–Whitney U tests throughout. For none of the four tuning alternatives was there a significant difference in preference for the tuning as a function of the participants' choral background (for all, $p > .05$, $N = 92$).

Yet, there were three background variables left: *gender*, *instrumental experience* and *age*. Normality tests or pitch drift preferences, local tempering preferences, equal temperament preferences, and meantone tuning preferences explored by *gender* are presented in Table 51 in Appendix 18. Because of the majority of non-normal distributions, the analysis went on with nonparametric Mann–Whitney U Test. As a result, there were found no statistically significant differences between genders for none of the four tuning alternatives (for all, $p > .05$, $N = 92$).

When it comes to *instrumental experience*, nonparametric Spearman's ρ test, showed no statistically significant correlations between the variable *instrumental experience* and intonation preferences (for all, $p > .05$, $N = 92$). Further, according to Spearman's ρ test, there were no statistically significant correlations between *age* and tuning manipulation preferences ($N = 92$). However, the correlation between local tempering preferences and age was nearly significant ($\rho = .20$, $p = .056$, $N = 92$): The older the participants were, the more they preferred local tempering.

4.3.4 Comparisons of preferences between experimental blocks

It could be assumed that the participants of the Experiment 2 felt themselves comfortable when they started to listen to chord progressions with different tuning alternatives. Participants may have experienced the differences between separate samples as rather marginal. Then, after some repetitions, a participant may have begun to pay attention to the slight differences better than in the beginning. It is a worth exploring whether this might have been the case. Breaking down the means across the five consecutive blocks of the experiment sheds some light on this matter in Table 40.

Table 40. Tuning manipulation preferences (mean) divided over five experiment blocks.

Tuning alternative	Experiment block 1	Experiment block 2	Experiment block 3	Experiment block 4	Experiment block 5	All together
	1–6	7–12	13–18	19–24	25–30	
PD[1]	0.76	0.60	0.67	0.48	0.95	3.48
	N = 93	*N* = 93	*N* = 92	*N* = 93	*N* = 93	
LT[2]	1.68	1.76	1.32	1.92	1.25	7.92
	N = 92	*N* = 92	*N* = 92	*N* = 92	*N* = 92	
ET[3]	1.52	2.18	1.94	2.10	1.80	9.54
	N = 92	*N* = 92	*N* = 92	*N* = 92	*N* = 92	
MT[4]	2.04	1.45	2.08	1.49	1.99	9.05
	N = 92	*N* = 92	*N* = 92	*N* = 92	*N* = 92	

[1] PD = pitch drift, [2] LT = local tempering, [3] ET = equal temperament, [4] MT = meantone tuning

Both Kolmogorov–Smirnov test and Shapiro–Wilk test suggested non-normality for the distributions of all experiment blocks of the four tuning alternatives (for all, $p < .001$) which is seen in Table 52 in Appendix 19 (The results of normality tests for distributions of all experiment blocks of the four tuning alternatives in Experiment 2).

Nonparametric ANOVA (Friedman) showed there were found statistically significant differences between experiment blocks [$\chi^2\,(4) = 28.72, p < .001$] in pitch drift preferences. Further analyses with the Dunn–Bonferroni test for related samples revealed that there were statistically significant differences in pairwise comparisons between

experiment blocks 2 and 5 ($z = -3.08, p < .05$) and

experiment blocks 4 and 5 ($z = -4.27, p < .001$).

When it comes to local tempering preferences, there were statistically significant differences between experiment blocks [$F(4) = 41.26$, $p < .001$]. Further analyses revealed that there were statistically significant differences in pairwise comparisons between

experiment blocks 1 and 5 ($z = 3.05, p < .05$),

experiment blocks 2 and 5 ($z = 3.26, p < .05$),

experiment blocks 4 and 5 ($z = 4.71, p < .001$),

experiment blocks 2 and 3 ($z = 2.87, p < .05$), and

experiment blocks 3 and 4 ($z = -4.31, p < .001$).

When it comes to equal temperament preferences, there were found statistically significant differences between experiment blocks [$F(4) = 46.53, p < .001$]. Further analyses revealed that there were statistically significant differences in pairwise comparisons between

experiment blocks 1 and 2 ($z = -5.32, p < .001$),
experiment blocks 1 and 3 ($z = -3.22, p < .05$),
experiment blocks 1 and 4 ($z = -4.38, p < .001$), and
experiment blocks 2 and 5 ($z = 3.31, p < .01$).

Finally, concerning meantone tuning preferences, there were found statistically significant differences between experiment blocks [$F(4) = 61.42, p < .001$]. Further analyses revealed that there were statistically significant differences in pairwise comparisons between

experiment blocks 1 and 2 ($z = 4.83, p < .001$),
experiment blocks 1 and 4 ($z = 4.34, p < .001$),
experiment blocks 2 and 3 ($z = -4.80, p < .001$),
experiment blocks 2 and 5 ($z = -4.22, p < .001$),
experiment blocks 3 and 4 ($z = 4.31, p < .001$), and finally,
experiment blocks 4 and 5 ($z = -3.73, p < .01$).

Pitch drift was the most unpopular choice in every experiment block. In the last block (25–30) it was better accepted. Local tempering preferences varied most of these four alternatives (M varied from 1.25 up to 1.92). In the beginning equal temperament was preferred as often as local tempering, but from the second experiment item (chord progressions 7–12), it took its place as the most popular tuning manipulation. Meantone tuning preferences seemed to have two separate categories, M approximately = 1.5 and M approximately = 2.0.

It is very challenging to find the explanation for these differences. There were no signs of fatigue or adjustment of the participants. It is possible that there are some factors in chord progressions which explain these differences between experiment blocks.

4.4 Reliability and validity of Experiment 2

The recognition results of the experiment were also subjected to PCA. Rotation method was varimax. At first, according to PCA done for sum variables of pitch drift preferences, local tempering preferences, equal temperament preferences, and meantone tuning preferences, there occurred three components, which is seen in Fig. 35.

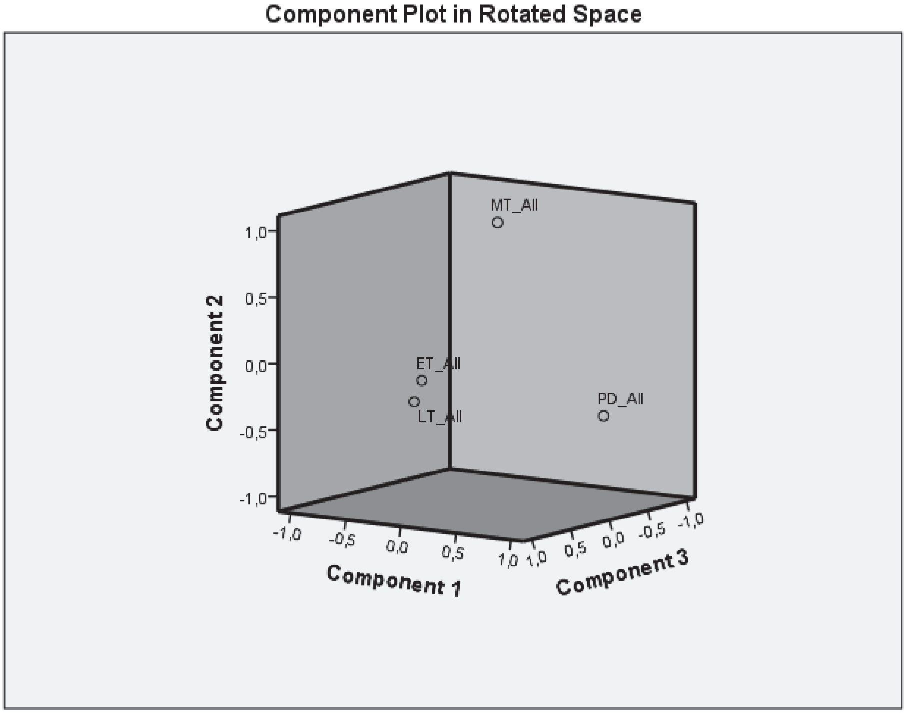

Fig. 35. Component plot in rotated space for pitch drift preferences, local tempering preferences, equal temperament preferences, and meantone tuning preferences by PCA.

Equal temperament and local tempering preferences constituted Component 1 in the PCA (see Fig. 35). According to this analysis, local tempering and equal temperament preferences were alternatives to each other against pitch drift preferences and meantone tuning preferences. This is somewhat surprising because these two alternatives have only one common feature of tuning: equally tempered second-degree minor triads. In local tempering manipulation all other vertical triads are assembled in just intonation. Instead, local tempering and meantone tuning alternatives have more common features: all major thirds are pure in meantone tuning alternatives used.

Next, according to factor analysis done for all experiment items (30) revealed even 13 factors according to rotated factor matrix of factor analysis. This result is slightly surprising. Only sum variables representing Factors 1 and 2 gathered loadings for four experiment items. The sum variables representing Factor 1 (.606), Factor 2 (.645) achieved a sufficient value of Cronbach's α, which means a reasonable internal validity of experiment items representing Factor 1, and 2.

Other sum variables representing other factors (Factors 3–13) did not achieve sufficient values of Cronbach's α for Factors 5, 6, 7, 9, 12, and 13, there was only one item with highest loading on them. They can be called as pseudo-factors. All loadings of Factors 1–13 are gathered in Table 41 below. The results of the factor analysis of the experiment items representing factors as variables are presented in Table 53 in Appendix 20.

Table 41. Experiment items for Factors 1–13, by factor analysis (rotated factor matrix) and Cronbach's α.

Sum	Factors												
variables	1	2	3	4	5	6	7	8	9	10	11	12	13
PD-ET3	.80												
LT-ET4	.73												
MT-PD4	.57												
PD-MT3	.48												
PD-MT1		.77											
ET-PD2		.74											
ET-PD4		.68											
MT-PD2		.48											
LT-PD5			.71										
LT-MT3			.68										
PD-ET5			.48										
ET-MT3				.80									
MT-ET4				.52									
MT-LT2					.87								
LT-ET2						.85							
ET-LT1							.80						
PD-ET1								.78					
LT-MT5								.69					
LT-PD3									.83				
LT-MT1										.70			
ET-LT5										.68			
LT-PD1											.76		
PD-LT2												.49	
ET-MT1													.86

PD = pitch drift, LT = local tempering, ET = equal temperament, MT = meantone tuning

To view the loadings of these experiment items, it seems clear that the four tuning alternatives do not measure four properties of participants. In seven experiment items of eight in Factor 1, and 2, pitch drift preferences are against equal temperament or meantone tuning. Once local tempering preferences "replaces" pitch drift preferences. pitch drift appears in seven factors in all. Interesting is that local tempering preferences appear in eight factor outside of Factors 1 and 2.

In the loadings of experiment items representing Factors 1–13 included loadings as following:

- Meantone tuning against pitch drift in four loadings
- Equal temperament against pitch drift in five loadings

- Local tempering against pitch drift in five loadings
- Local tempering against equal temperament in four loadings
- Local tempering against meantone tuning in three loadings
- Equal temperament against meantone tuning in three loadings

This variety of pairs shows that the only clear separable property of these experiment items representing different factors is pitch drift preferences.

The content validity of this experiment can be examined from the viewpoint of the tuning alternatives used in the experiment. These alternatives and preferences on them are interlinked: By choosing a certain alternative, one rejects other alternatives. This experiment does not measure a certain property which is connected to certain tuning. There were two traditional, well-known tunings and two innovative tuning alternatives. The differences between local tempering, equal temperament, and meantone tuning preferences were, as written before, were likely too small to produce more distinct results.

The criterion validity of this experiment cannot be estimated because, because there should be an alternative test which could be used as testing the preferences of the four tuning alternatives used in this experiment.

5 Discussion

This last main chapter has the total nine sub-chapter. At first, we come back to original research questions (see Sub-chapters 5.1 and 5.2). Then I will introduce practical implications on the ground of this book (see Sub-chapters 5.3, 5.4, and 5.5). After these experiments, it may be justifiable to ask, is there music without syntonic commas (see Sub-chapter 5.6). Description of ethical issues is taking place in Sub-chapter 5.7. Further, the insight of self-criticism is seen in Sub-chapter 5.8 (Critical observations of the present research). Finally, recommendations for further research, Sub-chapter 5.9, ends this book.

5.1 Answering the first and second research question

Experiment 1 (recognition of mistuning recognition) charted out the recognition of the syntonic comma. To refresh the memory, the first two research questions were the following:

1. To what extent do young music learners recognize mistuned triads in simple four-voiced just intonation harmony?
2. To what extent can the recognition of the mistuned triads be explained by a) musical features such as the complexity of harmony or the target location, and b) the participants' individual features (e.g., instrumental experience)?

The number of recognized mistunings (in the whole data set of 40 samples) varied from 8 to 35 recognition ($M = 22.97$, SD = 5.78, median = 24) out of total (40 samples): The participants recognized on average 57.43% of mistuned triads. This is, of course, clearly more than at random which means that young music learners do have sensitivity to perceive this kind of mistuning. The recognition percentage was highest (.92) in Trial 35 (CAT1/6). and lowest (.22) in Trial 9 (CAT2/9). The range of distribution was rather broad. The finding of Schellenberg (2001), going out of tune is more conspicuous than going in tune, was present in this study: participants detected mistuned triad among the pure ones.

As mentioned in 2.2.8., thresholds for pitch discrimination between 2 cents and 20 cents for musicians in several investigations in recent years, so that the result of the first research question was in line with previous studies. Thresholds for simultaneous tones can vary from 2 cents (complex tones) to 50 cents (low-level pure tones) according to Burns (1999). Ballard (2011, p. 30) reminded that the difference limen for pitch perception is between 3 and 8 cents. In this experiment, the mistuning of 21.51 cents was broadly detected. The results are better than in the findings of Vurma (2010) where 34% of singers recognized a mistuning of 20 cents and better than in the study of Schellenberg and Moreno (2010) where musically trained scored a mean threshold of 41.63 cents and 43.92 cents (detecting mistuning from two familiar melodies). Of course, the design of these experiments was not similar.

The finding of Dunnigan (2002) and Schellenberg (2001) that flat fifths are easier to accept than sharp fifths, may not have been supported. The flat fifths of the second-degree minor triad were recognized as mistuned quite well. In the study of Koelsch et al. (1999), professional violinists detected 80% of mistuning (−12 cents in the third of the major triad) in simultaneous triads which is a better result than in the present study. However, Koelsch et al. (1999) studied professional musicians whereas the present study was done for young music learners.

Interestingly, Larrouy-Maestri (2018) found the measured tolerance concerning the subjects' tolerance with regard to mistuning across six-tone melodies, the mean tolerance threshold was approximately 21 cents, which is practically a syntonic comma. Although, Larrouy-Maestri studied melodic mistunings.

Concerning research question 2a, I found that complexity influenced the recognition of the target. Mistuning was recognized best in the simplest category (Category 1): 66.77% of the targets were recognized. Although the best mistuning-finders were very skillful, it is impossible to predict their pitch-matching skills on the basis of pitch discrimination skills. It seems strongly that good pitch discrimination skills do not guarantee an accurate performance (Ballard, 2011; Bradshaw & McHenry, 2005; Kopiez, 2003; Powell, 2010; Vurma, 2010; Yarbrough et al., 1995).

The target was recognized worst in the most complex category (Category 3): The participants recognized 42.6% of mistuned targets. Category 2 was in the middle: The participants recognized 54.1% of targets. The differences between categories were significant: The confidence intervals of means and medians of separate categories were not overlapping.

The results showed that Category 2 was split in two: The target was recognized better in chord progressions with the syntonic comma in melodic movements when compared with those chord progressions without melodic commas. This finding was significant: The confidence intervals of means and medians of these two groups of Category 2 were not overlapping. Studies regarding the influence of the complexity of musical material on detecting mistuning were not found among the literature reviews of this research.

It was also a purpose to investigate, still according to research question 2a, how the location of the target (four locations) affects the recognition of the target. The results showed a significant difference between Location 2 and 3: The confidence intervals of means and SDs were not overlapping between Location 2 and Location 3. Location 2 was clearly the worst for recognizing mistuning, Location 3 was best. One possible explanation for this is that position 2 was the kind of perception point, in which the listeners might have perceived to rhythmical change from half notes to quarter notes: Target in position 3 might have been easier to perceive. This, however, would need further investigations.

It was interesting to see to what extent the participants misattribute mistuning to a pure minor and major triad. Mistuning was misattributed to a minor triad in 24.73% of cases and to a major triad in 18.88% of cases. Concerning the misattributions to a minor triad, the confidence intervals of means were not overlapping between Category 1 and 2, between 2 and 3, and between 1 and 3. The confidence intervals of median were not overlapping between 1 and 3 and between 2 and 3. Concerning the misattributions to a major triad, the confidence intervals of means and medians were not overlapping between Category 1 and 2, between 2 and 3, and between 1 and 3. It can be claimed that the distributions of categories were situated in different places. It is a little bit comforting that there were more mistuning misattributions to minor triads than to major triads (median = 5, Mode = 4, *M* = 5.47). Elements of major triad are based directly to harmonic spectra. Minor triad is, instead, a more complicated phenomenon. It was presumable that there would be clear differences between three categories in misattributions to a major triad, too. Misattributions to a major triad in Category 3 were understandable: Modally altered, but vertically pure major triads have misled several participants. Modally altered major triad has somehow sounded "weird" or "wrong" and a part of participants has misattributed mistuning to a modally altered major triad. This, of course, explains low values in misattributions to a minor triad in Category. In the case of misattributions to a major triad in Category 3, the difficulty of recognizing correct intonation (Baker, 2010; Hedden & Vurma, 2010; Rasch, 1985; Siegel & Siegel, 1979; Vurma & Ross, 2006) were somehow supported.

Research question 2b) handled background variables and their effect on recognition of mistuning: a) the instrument group of main instrument, b) the voice that the participant sings in choir, c) gender, d) age, and e) instrumental experience (measured in years). According to findings, participants' main instrument did not seem to affect recognition of mistuning nor misattributions to a minor triad or major triad. There were no significant differences between how well participants representing different instrument groups succeeded in localizing the mistuned triads. The same was true separately for each of the stimulus Categories 1–3. There were no statistically significant differences between choir voices in recognition of mistuning in the whole data set nor in Category 1 or Category 3, either. Instead, in Category 2 and in the set of melodic commas (in Category 2), there was a statistically significant difference between top voice singers and bass voice singers: Bass voice singers detected mistuning better.

There were no statistically significant differences between male and female participants in recognition of mistuning, nor in separate categories.

Several connections were found between recognition of mistuning and instrumental experience and age. The findings of several investigators (Dunnigan, 2002; Koelsch et al., 1999; Micheyl et al., 2006; Parbery-Clark et al., 2009; Schellenberg & Moreno, 2010; Slater et al., 2018; Spiegel & Watson, 1984; Strait et al., 2010; Tervaniemi et al., 2005) were supported: The musical experience increase pitch-discriminating skills. Instrumental experience and age together explained 29.3% of recognition of mistuning in the whole data set: When age increased by one year, recognition of mistuning increased by 0.46 unit element. When instrumental experience increased by one year, recognition of mistuning increased by 0.36 unit element. The results were parallel in Categories 2 and 3. However, there were no statistically significant connections between recognition of mistuning and instrumental experience and age in Category 1.

Age and mistuning misattributions to a minor triad were inversely connected. The older the participants were, the less they misattributed mistuning to a minor triad. The connection between mistuning misattributions to a minor triad and instrumental experience was not statistically significant. When it comes to misattributions to a major triad: The older and more instrumentally experienced the participants were, the less they misattributed mistuning to a major triad.

Age and instrumental experience had a strong, positive correlation. Mistuning recognition was positively correlated to both of these variables. This was seen also in separate categories of recognition of mistuning. Respectively, the correlations between mistuning misattributions to a major triad and age and instrumental experience were negative in the whole data set and in separate categories. Concerning the misattributions to a minor triad, the correlation was negatively significant in the whole data set and in Category 1 and practically in Category 2. Instead, Category 3 was the exception: there was no a statistically significant correlation between mistuning misattributions to a minor triad and instrumental experience and mistuning misattributions to a minor triad and age in Category 3. When it comes to recognition of mistuning, again, factor analysis revealed loadings from Categories 1 and 3.

Music analysis explanations for the differences between participants in the recognition of the target were hard to find. Marmel et al. (2008) found that tonally related targets were discriminated more sensitively than tonally less related. However, the chord progressions were composed to be functionally possibly neutral. It was not observed that some "more" traditional chord progressions would have stood out from results.

As remembered, bright tones were perceived sharper than dull tones (Geringer & Worthy, 1999; Vurma et al., 2011). The results could have been different, if the sound was duller. Ballard (2011) found that, pitch discrimination does not seem to depend on tuning system. It would have been interesting to investigate, whether there would be differences recognizing mistuning if the pure triads were in equal temperament.

5.2 Answering the third and fourth research question

According to the third research question, my purpose was to clarify, which usages of the syntonic comma university music students and professional music educators prefer in tonal and modal four-part texture? To answer the third research question, one must ask, how intonation preferences were distributed among the four tuning alternatives pitch drift, local tempering, equal temperament, or meantone tuning. The results showed that there was an overall rejection of pitch drift preferences: pitch drift preferences had the clearly worst success ($M = 3.48$). equal temperament preferences ($M = 9.54$) and meantone tuning preferences ($M = 9.05$) were almost equal. local tempering preferences ($M = 7.92$) were clearly above pitch drift but not so far away from equal temperament and meantone tuning. If one of the four tuning alternatives (pitch drift, local tempering, equal temperament, and meantone tuning) would have always been found more preferable to each of the three alternatives, it would have reached at maximum value of 15. These values are interlinked, or course: If one chooses one alternative, one rejects another. The shunning of pitch drift is somewhat different result from finding of Hancock (2008): The gradual change of pitch did not seem to bother the most listeners.

Aforementioned results conform the findings of Long (2008): Equal temperament turned out to be preferred over other tuning alternatives in most passages: The selection of one intonation systems preferred over another seemed not to occur accidentally. The acceptability of equal temperament and meantone tuning could resonate the finding of Nordmark and Ternström (1996): Experienced musicians preferred major thirds (mean 395.4 cents) closer to equal temperament than just intonation. local tempering and meantone tuning had pure major thirds in chord progressions, which might indicate the preference for consonance and non-beating chords supporting the finding of Johnson-Laird et al. (2012) regarding that major triad was the most consonant chord (rated 1.67) whereas minor triad had a rated dissonance of 2.41.

How were the preferences of the six comparisons of the four tuning alternatives distributed? When pitch drift was compared to equal temperament (85.2%) and meantone tuning (85.9%), pitch drift was clearly and significantly shunned. local tempering gathered 59.8% from preference judgments against pitch drift. equal temperament and meantone tuning were practically equal. Equal temperament was slightly more preferred compared with local tempering. It is a bit surprising that local tempering was slightly more preferred against meantone tuning, but the result was not significant. The results are understandable remembering that equal temperament has been found a typical reference system among wind instrumentalists (Duke, 1985; Karrick, 1998; Kopiez, 2003; Leukel & Stoffer, 2004). On the other hand, aiming at just intonation was seen in studies of Karrick (1998) and Leukel and Stoffer (2004) and with singing ensembles in vertical thirds in the study by D'Amario et al. (2018). In practical situation of singing ensembles and choirs, pitch drift can happen (Fischinger et al., 2015; Howard, 2007a, b) or not (D'Amario et al., 2018; Devaney et al., 2012), but offered as aural sample with a synthetized sound, it was not accepted very well.

I also clarified, how the interlinked preferences of tuning alternatives are related to each other. There was a strong, negative correlation between pitch drift preferences and equal temperament preferences: The more participants preferred equal temperament, the less they preferred pitch drift. The more participants preferred meantone tuning, the less they preferred pitch drift. The more participants preferred equal temperament, the less they preferred local tempering. The more participants preferred meantone tuning, the less they preferred local tempering. The more participants preferred meantone tuning the less they preferred equal temperament. The negative correlation between equal temperament and meantone tuning preferences can be interpreted as alternatives for participants.

As known, sharp tendency seems to be true among the performances of string instrument players (Bohrer, 2002; Burns and Ward, 1999; Byo et al., 2011; Fyk, 1998; Kantorski, 1986; Sundberg, 1982). In this experiment, "sharpest" tendency was in equal temperament which was barely the most favored. It is a question worth speculating, how Pythagorean tuning would have been preferred in this comparison.

The fourth research question was the following: To what extent can these preferences be explained by the participants' individual features (e.g., choral experience)? These individual features were the following: A) choral background, B) gender, C) age, and D) instrumental experience.

For none of the four tuning alternatives was there a significant difference in preference for the tuning as a function of the participants' choral background. There were found no statistically significant differences between genders for none of the four tuning alternatives, either. There were found no statistically significant correlations between the variable *instrumental experience* and intonation preferences. There was almost a same situation between *age* and intonation preferences. Almost significant correlation was found between local tempering preferences and *age*. The older the participant was, the more he/she preferred local tempering.

When the means across the five consecutive blocks of the experiment were broken down, there occurred several significant differences between experiment blocks in pairwise comparisons. Pitch drift was the most unpopular choice in every section. In last section (Trials 25–30), it was better accepted. Local tempering preferences vary most of these four alternatives (*M* varied from 1.25 up to 1.92). In the beginning equal temperament was preferred as often as local tempering, but from the second experiment item (chord progressions 7–12), it took its place as the most popular tuning manipulation. Meantone tuning preferences seemed to have two separate categories, *M* approximately = 1.5 and *M* approximately = 2.0.

5.3 Practical implications from Experiment 1

The third objective of this dissertation is to find out, how the usage of the syntonic comma, as assembled in Experiment 1 and 2, could help in teaching intonation skills in music education. The results of Experiment 1 and 2 gave some practical implications which I introduce in the following Sub-chapters 5.3.2 and 5.3.3. In addition, there will be some practical implications based on research literature concerning intonation issues from the music education point of view in Sub-chapter 5.5. Which factors do influence pitch matching? How to improve intonation in practical situations of music? Practical implications are introduced in Sub-chapters 5.3, 5.4, and 5.5.

As a conclusion, the Experiment 1 showed that the complexity of the musical material affected the recognition of mistuning which gives motivation for the development of new exercises for intonation skills. Mistuning was detected very well in simple harmony. This sensitivity of listeners indicates that aiming to better intonation is possible. Instrumental experience and age were positively connected with the recognition of the mistuned triad and this fact suggests improvement of intonation skills in music pedagogy of all levels. Some clues were found according to which the choir voice the music learner sings might affect the ability to recognize mistunings. This, however, needs further studies.

The results of the Experiment 1 showed that the distribution of recognition of mistuning in the whole data set was broad. It means that pupils in music-intensive classes are differentiated in relationship with harmonic discrimination. This experiment showed that the complexity of musical material influenced the recognition of mistuned triad. The high values of recognition (over 90%) in the simplest chord progressions indicate that it makes sense to strive for pure intonation always when it is possible. The mistuned triads were recognized very well, in places, which gives a concrete tool to illuminate to problem of the syntonic comma in music pedagogy. When it has been illuminated by pedagogical tools, the next level is to learn tools to eliminate it.

As an unexpected result of the Experiment 1 was that the distribution of recognition of mistuned triad was broad. This experiment separated the participants effectively. It means this experiment might be used as part of entrance examination to professional music studies. This needs, however, further investigations.

A syntonic comma in melodic movements in Category 2 produced an unexpected result: The target (vertically mistuned triad) was detected better, if there was a syntonic comma also in melodic movements. This could be the key to open a deep discussion of harmonic and melodic intonation and it should be investigated more. It is possible to construct intentionally such harmonic progressions where the mistuning of the syntonic comma is assembled only into melodic line while vertical harmony staying pure. Which one disturbs more: mistuned vertical chords or mistuning in melodic lines?

One clear observation of this experiment is that age and instrumental experience have a strong relationship to recognition of mistuning. This is, of course, not surprising at all but strengthens the motivation to develop learning tools of intonation skills in music education. If learning music theory is based on only equally tempered music, it may be misleading in relationship with many aspects. The chord progressions of the experiment of recognition of mistuning (or the corresponding ones) could be used in illuminating except the syntonic comma, but also the elements of intonation. It would be completely possible to create a lively learning material for ear training and music theory, which keeps intonation issues attached from the beginning of learning. Young children could be accustomed to pure triads in singing and playing if the teacher is aware enough of intonation issues. The question of the syntonic comma could very well be presented for a 12-year-old child attached to ear training and music theory. The demonstrations of different temperaments and tuning alternatives can be performed with simple synthesizer.

The idea of the experiment of intonation preferences was partly based on the findings of Howard (2007) and Howard et al. (2013). He reminds that good listening skills are important. He thinks that the following manners are not recommended when aiming at just intonation: Choir practice with instruments tuned in equal temperament, listening equal temperament music, working with conductors, who are unware of tuning implications, presenting an equal-tempered chord to start the piece, being trained to remain in tune, and poor listening skills (Howard, 2007a, p. 93).

It is extremely difficult to avoid listening to equal-tempered music. But in acoustic ensembles and choirs, the awareness of complexity of intonation issues may help player and singers to aim better intonation, which is not totally based on equal temperament. Otherwise the recommendations of Howard seem to make sense.

The experiment of recognition of mistuning turned out to be a functional method to measure, how well student and pupils can recognize of the mistuned minor triad. In music education, it could be more. These kind of chord progressions can be a tool for harmony analysis and voice leading. But above all, this set of chord progressions is a functional tool for a pedagogy of intonation systems. Just intonation, the syntonic comma, tempering, mistuning, just few mentioned. The set of samples could be used for literal tasks, audible analyzing and even singing and playing. Four-voiced singing of samples including a syntonic comma could open one’s eyes (and ears) for pure intonation as well as the strategies for tempering. A distant concept of the syntonic comma would awake for students and pupils to work on.

5.4 Practical implications from Experiment 2

As a conclusion: The results of Experiment 2 give new possibilities to increase the awareness of different temperaments and tuning alternatives. Professional music students were ready to accept old tuning method (meantone tuning) as well as the most familiar equal temperament which surrounds us all over the Western world. The results of preferences of local tempering were also encouraging to develop new means for dealing with the syntonic comma in modal/tonal material.

In the Experiment 2, pitch drift executed in one change of chord, caused suspicion. It is difficult to imagine that the demand on stable pitch would easily loosen. Many choral conductors use equally tempered piano to support the learning process. Unfortunately, this does not support the development of fine adjustments of choral intonation. As worst, an amateur choir may use it during the whole process. Singers never hear the purest alternatives of harmony. According to Howard (2007b, p. 315), if choral conductors want to achieve consonant tuning, they should avoid piano in rehearsals and give only the tonic of the first note in the beginning of the performance piece.

Howard et al. (2013) argue that the overall pitch drift can cause confusion among choir leaders which can lead to use of equal-tempered tuning reference in choir rehearsal: That is not the way to achieve the most pleasant sound and maximum consonance. He continues that the most skillful choirs may allow the ‘pitch drift’ to achieve the most consonant intonation of chords singing a cappella. (Howard et al., 2013, pp. 136–141).

Tuning alternatives of the experiment of intonation preferences can be divided in two categories based on how the dilemma of the syntonic comma is solved. In pitch drift, the syntonic comma causes pitch drift in the second-degree minor triad: The fundamental pitch rises or falls by a syntonic comma. 1) The usage is local, it is tar geted to one chord. In local tempering, the usage also is local: One (mistuned) chord is manipulated in an otherwise standard tuning system, equal temperament. Instead, the fixed temperaments, equal temperament and meantone tuning, distribute the mistuning due to the syntonic comma throughout the scale: 2) The usage is global. As explained in Sub-chapter 2.1.6., equal temperament divides comma in equal parts, meantone tuning distributes it in in various parts of the scale in different amounts.

In the present experiment, the local usages (pitch drift and local tempering) were preferred by the participants less other than either equal temperament or meantone tuning. Fixed systems with global usages thus appeared to be more readily acceptable to the listeners than systems with local alternatives. In practical terms, equal temperament and meantone tuning can be considered as equal in favor. On the other hand, local tempering preferences toward meantone tuning preferences, produced a surprise (local tempering = 54.6%, meantone tuning = 45.4%): the difference was almost significant. As mentioned, equal temperament was significantly more preferred toward local tempering.

It can be considered as a one clear result of the Experiment 2 that the music educators were shy of pitch drift in tonal and modal musical textures. All comparisons involving pitch drift suggested that the listeners tend to avoid the sound of pitch drift in favor of other possibilities. In comparison, the other three tuning alternatives were notably better accepted.

It was not unpredictable that pitch drift was turned down by the listeners. There does not seem to exist a tradition of pitch drift for instance in choral singing. If the fundamental pitch changes during a choral performance, it is likely to be judged as a failure, if indeed it is noticed at all. It is not very well known that pitch drift could also be a sign of purely sung vertical chords rather than just evidence for the lack of skill on the part of the singers.

Following the views of Howard et al. (2013) the use of equal temperament could perhaps be somehow updated. It could be freshening to try earlier temperaments or why not, new innovations in some occasions. For example, simple exercises in ear training lessons, in warm-ups, in instrumental lessons, only few examples to be mentioned, could be accompanied with local tempering or meantone tuning. The ordinary praxis has shown that the most of the warm-up exercises constitute of notes triads with rise–fall method. Or singing scale upward and downward. There is no reason why this kind of exercises should be run with equal temperament. The traditional just intonation itself could be the basis of these exercises. The keyboard used through local tempering could be used in most warm-up exercises and in harmonically simple songs. The most of the chord could be sung purely.

Pitch drift could be allowed when a choir or vocal group exercises pure vertical chords. It is practically very demanding but improving. If pitch drift arises with singing group in particular chord progressions, it is a very concrete illustration for the syntonic comma.

Local tempering is possible and usable due to well-developed technology. The audio samples where ii triads were converted to equal temperament were fairly simple to generate. Of course, a locally changeable temperament cannot by definition be applied as a fixed tuning system in, say, a keyboard. It is very easy to program a new temperament to a digital synthesizer. This does not have to be a keyboard. It is possible to use synthesizer rack and connect it to any digital keyboard anywhere. But this tuning manipulation, local tempering, would require a separate software. All pitch classes of the ii triad are, in this manipulation, “stolen” direct from equally tempered scale. So, their exact pitches vary slightly from those of just intonation scale. The software should recognize ii chord played and give always pitches corresponding to equal temperament. Respectively, those pitch classes as a part of other chords, should stay in just intonation scale.

Local tempering as an innovative tuning system, was not, in general, rejected by the participants in this limited experiment. It could be used anywhere where the musical material is simple enough.

Local tempering could be an alternative adaptive tuning developed by (Sethares, 1994). It is a method of dynamic adjusting for the pitches of note, called an *adaptive tuning*. It maintains fidelity to a desired set of pitches and intervals, and it can be modulated to any key. This invention is algorithm-based method which changes the pitches of notes to maximize consonance during musical performance. The system can be operated in real time and it is responsive to the notes played. The adaptive tuning is a kind of generalization of the methods of just intonation in two ways. It is independent of keys and it can be applied to common harmonic as well as to timbres with nonharmonic spectra. This method does not require specific musical knowledge. It retains both consonance and the ability to modulate. The expense of the system is the microtonal adjustments in the pitch of the notes. The timbre and the piece of music performed determine adaptive tunings (Sethares, 1994, pp. 14–17).

One could easily conclude that meantone tuning should be used when it is historically justifiable: in music from late Renaissance and early baroque periods. In such contexts, there is no excuse to replace meantone tuning with equal temperament. At least the listeners of this experiment would seem to have accepted meantone tuning as well as they accepted equal temperament.

Experiment 2 as a tool of teaching intonation skills

The experiment of intonation preferences turned out to be a functional method to chart out musician's preferences for intonation choices. In addition, it could be functional also in teaching different tuning systems audibly for pupils and students. Above all, it would an innovative demonstration for pitch drift. Understanding this phenomenon helps pupils and students to extend their intonation awareness. Pitch drift illustrates the syntonic comma. Almost in studies of conservatories and among university music students, student could make small intonation analyses in small samples including pitch drift.

5.5 Practical implications from pedagogical motivations

In addition, as remembered from Sub-chapter 2.4, there are several inventions and methods to improve intonation. Music educators are recommended to apply these findings of research literature. The following sub-chapters include summarized knowledge to apply intonation issues to practice flavoured with my experiences.

5.5.1 Factors influencing intonation: Summary

I will create a short summary concerning factors influencing intonation from the basis of previous research on pedacogical motivations (see Sub-chapter 2.4). This question is here considered from the viewpoint of choirs, wind bands and orchestras and general factors.

Choirs

There are a number of factors influencing pitch matching in performances. Concerning singing voice, the next factors influence the intonation: Breath support, vibrato in choir; articulatory perturbation of pitch singer spacing and room absorption on the self-to-other ratio, common partials, high partials, vibrato, and the interval (Ternström & Karna, 2011; Ternström & Sundberg, 1988). Fischinger et al. (2015) found that intonation is only a weakly influenced by room acoustics (varied room acoustics, three levels). The pitch can differ a bit in the left and right ears. The intrinsic pitch, the pitch-amplitude effect, breath support and complex modulations can affect the choir going out of tune (Ternström & Karna, 2011; Ternström & Sundberg, 1988). Demorest and Clements (2007) found that the choice of matching task, suitability of singing register, and tasking conditions, can influence pitch matching. The gestures influenced positively on pitch-matching accuracy among children in choirs (Liao, 2008; Liao & Davidson, 2016). Gestures and/or movement training influenced positively on singing in tune (Liao & Davidson, 2016).

To my experience, all these factors seems to be true. Especially strong vibrato of classically educated singers in choir singing makes aiming good intonation challenging. Gestures, in right amount, seems really effective especially among children choirs. On the other hand, I have seen a few conductors, who mostly disturb singers with lively gesturing.

Wind bands and orchestras

Schlegel and Springler (2018) had recommendations to wind band educators. 1) Teachers should offer players sound models which are in tune and out of tune. 2) The use of chromatic tuners (to adjust instrument length at the starting phase of rehearsals. 3) Students should have a possibility to train pitch discrimination and pitch matching separately because of these skills seem to be discrete abilities (Schlegel & Springler, 2018). Tuba sound was not an appropriate reference stimulus for mass tuning (Byo et al., 2011).

Jagow (2012) listed the factors influencing the intonation by wind players: Air, posture, embouchure, mouthpiece, amount of mouthpiece, angle of mouthpiece, lay of mouthpiece, barrel and bocal length, horn hand positions, tongue positions, reed condition, equipment, dynamics, pitch concept, balance, timpani pitch, percussion, and temperature. The lowered external temperature lowers the pitch (Powell, 2010).

Garofalo (1996) listed 10 factors that may cause poor intonation in band and orchestra performance: 1) Condition and quality of the instruments and accessories, 2) basic playing procedures, 3) insufficient warm-up (wind instruments), 4) playing of the standard tuning frequency (wind instruments), 5) psychological and musical phenomena, 6) pitch tendencies of instruments and performers, 6) poorly trained ears (students with little or no ear training), 8) poor balance (vertical dynamics), 9) poor seating arrangement, and 10) poor acoustics in the rehearsal and performance environments.

As flute player and wind ensemble conductor, I may say: “Been there, done that.” For instance, one single (cheap) unqualified wind instrument can ruin a remarkable amount of efforts achieving correct intonation. Cold circumstances for wind ensembles playing in patriotic events are familiar to most wind players in Finland. In the relation of “poorly trained ears,” to my experience, there are a lot of possibilities to make.

General factors

Kopiez (2003) found a few more affecting pitch matching: musical context, timbre, register, dynamics, beat frequencies, tone durations, size of intervals, effects of partial position of pitch production, and pitch classes. Worthy (2000) found that tone quality influenced the performed concert pitch and “bright” tones were judged sharper in pitch and “dark” tones flatter in pitch. He also noticed that woodwind groups performed sharper than brass groups. Morrison and Fyk (2002) discovered that specific feedback improves the pitch matching better than instructions alone. Accurate and inaccurate visual feedback influence the tuning accuracy of high school and college trombonists. Instrumental experience improved tuning accuracy (Schlegel & Springler, 2018).

I have heard numerous brass quintets and wood wind quintets and the finding of Worthy (2000) sounds familiar. Brass ensembles, on the whole, can achieve in right guidance justly intonated vertical chords.

5.5.2 Improving intonation: Summary

I have picked up some methods from the basis of previous research on pedacogical motivations (see Sub-chapter 2.4). Beat elimination, algorithms for pitch matching and other methods are discussed.

Beat elimination

Wuttke (2011) got to know that there are effective methods in intonation training: voice groups tune perfect intervals, building chords (root-fifth-third), performing chords ascending and descending by semitone, performing exercises and stopping on chords (identifying the partials of the chord), and using beat elimination process to build the awareness of intonation. Originally, Miles (1972) developed a well-working method of "beat elimination" and its utility has been noticed by Powell (2010), Kopiez (2003), Wolbers (2002), and Garofalo (1996).

The chord progressions of Experiment 1 in this dissertation, could be one way the practice to heat the beats only by listening. In real life, I have used this method of Miles (1972) without understanding the elimination of beats. Completely unprofessional players can learn to hear the beats in vertical triads, if they are guided correctly.

Algorithms for pitch matching

Stange et al. (2018) enabled the musician play in just intonation in any key with a dynamically adapting tuning scheme. Villegas and Cohen (2010) introduced a program for adjustable intonation: It aims at pureness to intervals (so close to beat-free sizes of intervals, as possible, just intonation intervals. Milne et al. (2007) invented a system which simplifies just intonation into system that can be controlled and played easily. They introduced keyboard fingering models to different tunings and keyboard fingering models for different tone order to several tuning systems, like 5-TET, 7-TET, 12 -TET and 17-TET and even models to different mean tone temperaments. Dalby (1992) developed the HITP.

I have use different temperatures simply assembling them into synthetisizer module. Of course, they are all closed systems, but the use of endless old temperaments is available with very simple technical operations.

Other methods for training intonation skills

Schellenberg and Moreno (2010) found that musically trained participants outperformed untrained participants in pitch-processing speed and relative pitch and frequency discrimination. Henry (2004) found that singers seemed to benefit of instructions using targeted pitch skills. Henry tested 15 pitch skills surrounding cadential, chordal and scalar tasks finding that both participant groups achieved significantly higher mean scores on the post-test than on the pre-test. Wolbers (2002) discovered that singing intervals and phares in the band rehearsals can improve pitch, balance, and musical syntax. Pasqua (2001) developed a method to increase intonation awareness and improve tuning skills during regularly scheduled instrumental lessons and it was designed in a cooperative learning model using four phases of tuning activities. Fogarty, Buttsworth, and Gearing (1996) reported the lack of motivation in intonation training tests. Among woodwind instrumentalists, knowledge of directional mistunings improved tuning accuracy of wind players (Yarbrough et al., 1995).

Garofalo (1996), again, has listed procedures helping to improve intonation: Treating intonation awareness of players, demonstrating “in-tuneness” and “out-of-tuneness,” requiring intonation charting with electronic tuner, teaching theory fundamentals and ear training, teaching singing, maintaining constant temperature and humidity, assigning parts for good balance, experimenting with seating (in orchestra), and refining warm-up and tuning procedures.

There are also avoiding training methods: Playing one note alone does not improve player’s intonation (Morrison, 2000; Yarbrough et al., 1995). Playing one note. I have experienced this several times through decades. This can better your embouchure but not your intonation.

5.6 Music without syntonic commas

The esteemed reader of this dissertation might conclude that singers or instrumentalists cannot escape the syntonic comma anywhere where Western music (triads including) exists. In a sense, one may say so. In fixed temperaments, like keyboards, the syntonic comma is very effectively “hided” by spreading along the chromatic scale of octave. But in most cases, where triads are somehow present in acoustic musical situations with possibilities to adjust pitches without steps, the syntonic comma occurs in chord movements. If performers, for example in vocal ensembles, prefer vertical purity and beat minimization, the part of melodic movements has to be altered by a syntonic comma. In addition, pitch drift may happen. If singers prefer melodic logic for instance in the direction of equal temperament, or even sharper direction, at least the part of vertical chords has to be tempered. In certain circumstances, say, in clear tonal material of in four-part texture with typical tonal cadences, the syntonic comma is an inevitable discrepancy of intonation. Hopefully, the present research has enlightened the essence of syntonic comma in Western tonal music.

However, there are some musical material to be performed in just intonation without the concern of dealing with the syntonic comma. In Renaissance period, a selection of harmonically simple material was found to be sang with purely tuned intervals and triads. The secret of these works is that typical tonal cadences were not needed. Two pieces of sheet music including vertical and horizontal intonation analysis are presented in Appendixes 21 and 22. Everyone can compose more music beyond the clear limits of just intonation.

5.7 Description of ethical issues

In both experiments, the listeners were informed consents. In Experiment 1, the most participants were underaged. The permission of research was asked from the corresponding office holder of school administrative. The informing presentation and approval form (see Appendix 2) were sent to guardians of the pupils under 18 years. Only the pupils with approvals took part to the experiment. The research was not a part of normal activity of school or teaching unit. The participants of the Experiment 2 were grown-ups. Participants in both experiments had an opportunity to interrupt the experiment, if they wanted. Nobody did.

The participants of both experiments listened to audial stimuli in the form of chord progressions. In Experiment 1, the participants were asked to answer (literally), what is the most mistuned/out-of-tune chord in the chord progressions performed. The audial stimuli were performed digitally, and they were listened by headphones. The volume of samples was less than 80 dB, and it did not cause any harm. In the Experiment 2 the participants were asked to answer (literally), which one of two chord progression manipulated by different ways they preferred. The duration of a sample in both experiments was approximately 10 seconds. The necessary rest between the sample pairs was five seconds.

The experiments of this research did not cause the damage for the participants. So, there was no safety threat for participants. Nor there was an exception of principle of permission based on knowledge. The integrity of participants of Experiment 1 and 2 was guaranteed under experiment conditions.

5.8 Critical observations of the present research

The data collection of this research was rather complex and lengthy process. At first, it was the purpose to investigate professional musicians Experiment 1. 335 professional musicians were invited with careful messages and administrative help. Once I met a whole orchestra (60 musicians) and got an opportunity to perform the research concept mutually. Seven professional musicians of total 335 from three organizations accepted the invitation. All this left me an impression, according to which recognition of mistuning among professional musicians may have been a sensitive subject of research. Perhaps measuring the recognition of the key ability of intonation caused a feeling of inconvenience. Unfortunately, I had to change to target audience. It would have been extremely interesting to investigate professional musicians but perhaps someone will succeed in it better than author.

If this research was started from the beginning, there would be quite many things to be do in a different way. The fundamental idea of the experiment of recognition of mistuning is functional. Musical material was divided into three categories along the complexity of musical material. The simplest category (1) and the most complex category (3) worked very well. The results showed that the material was logically composed and usable. Instead, Category 2 divided in two in recognition of mistuning: chord progressions with melodic commas and chord progressions without melodic commas. It would absolutely been wise to confirm a separate category which includes chord progressions with melodic commas only. In the early stage of this PhD project, there were no less than 72 chord progressions composed for this experiment. There were also Categories 4 and 5. Category 4 included 12 chord progressions, which all had melodic commas in one chord movement. On the other hand, there were no vertically a mistuned second-degree triad and this was the reason for omission of this category. But the Category 2 with melodic and harmonic commas would have been needed simply because melodic commas in Category 2 influenced the recognition of mistuning. In the present experiment syntonic commas in melodic movements turned out to be an essential factor although the research design was not imposed to them.

Category 5 included dominant septimal chords instead of the second-degree triad. There would have been a syntonic comma only between the fifth and the seventh of dominant chord. This category was ejected because of this. Dominant septimal chord has an ambiguous intonation. In the study of Sundberg (1982), the minor third located between the fifth and the seventh of the dominant seventh chord was extremely narrow, 276 cents. This showed that barbershop singers tend to aim at the intervals of harmonic spectra: The minor seventh of ratio 6:7 is 33 cents narrower than the corresponding value in the equally tempered scale (Sundberg, 1982, 60–61). In the present research, dominant seventh chords were omitted because of the ambivalent tuning alternatives.

Further, it would have been wise to include the same number of trials for each category. The better version of the Experiment 1 would have been like the following:

- Category 1, 10 trials (10 trials from 12 of Category 1 of Experiment 1)
- Category 2, 10 trials (6 trials from Category 2 of this experiment without melodic commas and four similar ones more)
- Category 3, 10 trials (10 trials from Category 2 with melodic commas)
- Category 4, 10 trials (8 trials from Category 3 of this experiment and two similar ones more)
- Category 5, 10 trials (10 trials with dominant septimal chord and the second-degree minor triad)

In addition, the misattributions to a minor triad or to a major triad were not completely purposefully designed. There were 10 chord progressions with the possibility to misattribute mistuning only to a major triad and one chord progression without any major triad to misattribute. These chord progressions were omitted from the data set of 29 experiment items. These 29 trials included 48 major triads and 39 minor triads. This weakened the comparability between misattributions. There should have been as many major triads and minor triads in addition to the mistuned target triad. It would have demanded three or five triads to be listened. One mistuned triad and one or two minor and major triads.

The other point of this experiment was originally to investigate professional musicians, university music students and school pupils. As mentioned, it was almost impossible to attract participants among the musicians. But it would have been extremely interesting to compare professional musicians and university music students and school pupils of music-intensive classes. In addition, the original thought was to run both experiments for all three groups of participants. The data would have been rich and these designs would have made possible to investigate potential connections between recognition of mistuning and intonation preferences of participants in three level. How these experiments materialized in reality were considerable compromises with respect to participants, and it can be considered as sort of failure.

I organized some unofficial pilots before the final research design concerning the experiment of recognition of mistuning. In my research process, a couple of sub-experiments gave some hints about influence of timbre to the mistuning recognition. The original plan was to execute the chord progressions with two different sound: the sini-wave sound and piano sound. The problems of attracting the participants made me to abandon this research design: I had to choose only one sound. Synthetic piano sound is closer to practical music education than sini-wave sound. In these pilots, I made attempts with different tempos and it did not seem to influence the recognition of mistuning. Hence, I chose a chorale tempo, 52 bpm into the final experiment.

When it comes to the basis of Experiment 2, a low reliability and validity of this experiment requires consideration. In Experiment 2 it would have been perhaps more informative if there were such tuning alternatives which differed from each other more than those tuning alternatives used. The differences between local tempering, equal temperament, and meantone tuning and especially local tempering and meantone tuning were obviously so small that the experiment did not completely measured such qualities it was intended to measure. For example, Pythagorean tuning would probably have been different enough to bring clearer results. Pythagorean tuning produces wide major thirds for I, IV and V triads and hence, high leading tone for dominant triad. Pythagorean tuning, local tempering, pitch drift, and some artificial tuning manipulation with mistuned elements would have brought interesting results. On the other hand, the alternatives used in Experiment 2 were natural alternatives which could have been used in real musical contexts.

The clearest imperfection of the design of the Experiment 2 was the selection of background variables. In the beginning of running process of this experiment, the participants were asked to describe their own musical background. As a result of these questions, the only valid criterion was choral background/no choral background. This process could have been planned more pedantically in relationship with choosing the participants. On the other hand, the recruiting the participants is challenging.

As mentioned in Sub-chapter 5.1, the variety of main instrument of participants was unilateral: the complete groups of instruments did not gather enough participants. It would have been wise to use an open question.

5.9 Recommendations for further research

Intonation in performance is a complex phenomenon. If there is an instrument with fixed pitch (like keyboard), the pitch matching of musician is wise to target to those fixed pitches. A cappella choirs, string orchestras, wind ensembles are much more complex. There is standard tuning frequency of A4 (440, 442, 444 Hz) and the rest is up to the player. Of course, the fingerings of wind instruments produce certain approximate pitches near equal temperament, but the accuracy of pitches is highly depended on blowing technique, temperature, acoustics, etc. A possibility to adjust pitches is common for all orchestral instruments excluding pitched percussion and harp. What is "pure" or "mistuned" depends of style period of music. This, in turn, is connected to complexity of harmony. Thick atonal harmonies require equal temperament. Instead of this, very easy tonal harmonies can be performed, of course, with equal temperament, but they, to my opinion, simply sound better using just intonation.

The conclusion made in the basis of the research literature of intonation in performance showed several possibilities for future potential. Three experiments would be needed. The participants of the experiments could be university music students divided in three groups. The first experiment group is called beat elimination –group (according to Miles, 1972). The second group, the comma group, would be taught by the method which is developed for this research and it is based on the syntonic comma –phenomenon.

The experiment of improving pitch matching

There are a few chord progressions to be sang by the groups. Most of the chord progressions can be singed/played in just intonation. There are also chord progressions which include chords with the discrepancies of the syntonic comma

(21.5 cents). In other words, some chords in chord progression cannot be singed/played in just intonation without beats. First, the purpose is to find out how effectively the participants can learn to play chords in just intonation and second, to find relevant strategies to avoid the problems of the syntonic comma in ensemble playing in those same tonal chord progressions. The intonation skills would be estimated by measuring the sizes of intervals of chord progressions in cents. The accuracy of intonation produces by the participants would be estimated by comparing the results with the just intonation intervals. In those chord progressions including syntonic commas, the estimation is focused on the strategies of tempering the syntonic comma in certain chords. The tempering of the "comma-chord" is successful when the fundamental pitch stays stabile. Strategies to avoid the syntonic comma are tempering: stretching or compress intervals in triads with syntonic comma.

The participants plays/sings a part of four-part harmony

There would be four tasks where the participants are asked to play a part of four-part harmony. The first task is to play soprano part. The second task is to play alto part. The third task is to play tenor part and finally the fourth task is to play bass. There are four different chorale-styled pieces in four-part harmony. This study would include three intonation experiments: The first one in the beginning, the second one after the first intervention, and the third one after the second intervention. Before the first intervention, the starting level of the intonation skills of students would be measured.

There would be basically two skills to observe and measure. First, the ability to produce beat-free intervals as a second tone of the intervals (1.8, 5, M3, m3) or as a part of a major triad or a minor triad. Second, the ability to temper triads with the syntonic comma (21.5 cents) would be observed and measured.

The beat elimination group would be trained to play/sing beat-free intervals and triads. The comma group will be trained to understand theoretically the principles of intonation in tonal music to aurally discriminate beat-free triads.

All the intervals would be played by both groups are measured and tabulated. The deviations from just intonation are measured and would be analyzed. The basic aim is to figure out how the chords with the syntonic comma would be handled. The tempering of chord including the syntonic comma has to be done somehow. It is also necessary to know, if the ensembles can produce beat-free chords in those chords, where it is theoretically possible.

The interventions needed

This study would include two interventions. Before the first intervention the intonation skills of the participants are measured with the experiment of intonation skills which is the first experiment. The first intervention: There would be two groups of participants. The first group is taught with beat elimination –method. The second group is taught with the comma method. After this, it is time for the first intervention. The second experiment is taking place after the first intervention in both groups.

Experiment 1 in the present research seemed to discriminate participants in the means of recognition of mistuning. It indicated that ability of recognize a vertical syntonic comma in the context of pure triads discriminated the participants of this study effectively. The by-product of this study was the fact according to which Experiment 1 measured cogently the one central aspect of intonation skills: the perception of pitch and harmony. There will be a gap of research to find out whether this experiment could describe some aspects of musicality. One possible research design could be a comparison of this experiment and some well-known and time-honored musicality test. This experiment could be supposed to be a noteworthy tool to measure certain aspects of musicality.

The question of harmonic versus melodic intonation needs further studies. For instance, one common conception in instrument pedagogy is "high" leading tones. By gut feeling, this is happening independently from the musical style, context, or harmony. Previous findings have shown that there is often a tendency for sharp intonation. However, it is rather clear to sketch an optimal intonation for limited, homophonic harmony to maximize pure intervals vertically. Yet, the melodic line above the harmony can be ambivalent for this intonation strategy. It could be thrilling to create experiment design where high leading tones are assembled to homophonic harmony. In my opinion, they do not sound good, I have tried. Professional musicians and instrument pedagogues would be the group of participants. If these high leading tones in harmony would be disliked, the pedagogy of intonation should be rethought. Possibly.

The influence of tempo to mistuning recognition should be studied, too. My unofficial sub-studies with two tempos did not seem to bring clear hints, but this should be studied properly.

Now, when the recognition of the second-degree minor triad is now charted out quite thoroughly, it would be reasonable to investigate the recognition of mistuning in major triads, too. For instance, the major thirds of major triads could be tuned into Pythagorean size (81:64 = 407.82 cents). The fifths could be tuned as “Wolf” (40:27 = 680.45 cents) or pure (3:2 = 701.96 cents).

The detection of mistuning could be investigated more precisely. The complexity of the musical material could be added to extremity: chromaticism of late Romantic period or atonal harmony. On the grounds of Experiment 1 it is possible that mistuning of the syntonic comma would not be perceived very well in such a complex harmonic context. It would be tempting to think that the harmonic context where the syntonic comma is not perceived could be a justification to equal temperament. Respectively, the harmonic context where the syntonic comma is well detected, should be the environment of just intonation or extended just intonation. This could, at best, formulate a theory of optimal intonation: The recognition percentage of the syntonic comma could determine an intonation system recommended to use, at least theoretically.

In addition, it would be interesting to find out, whether the mistuned triad by a syntonic comma is recognized in equal temperament context as well as in just intonation context. This could be a part of the series of experiment to formulate a theory of optimal intonation mentioned in previous lines. There could be a few experiments all measuring the perception of the syntonic comma. The experiment could include excerpts from Renaissance music, baroque period, classism, Romantic period and atonal music. The musical passages would be performed with maximum consonance in extended just intonation. When this is not possible (late romanticism, atonal music), the excerpts would be assembled to equal temperament.

If we stick in chord progressions used in two experiment of this dissertation, they could be investigated using singers and players. These chord progressions, or same type of chord progressions, could be played by participants. Because of the exact knowledge and transparency of the syntonic comma, it would be easy to create a research design where participants would sing or play those chord progressions. The main focus would, hence, be how participants solve the problem of the syntonic comma.

As written in Sub-chapter 3.4.1, the chord progressions used in the Experiment 1 and 2, were organized at basis of practical music theory. The modern cognitive neuroscience (e.g., Slater et al., 2018) could help future potential so that target to be perceived, could be more one-dimensional than it was in Experiment 1.

It seems that the equal temperament, from the basis of ordinary observation, assembled to electric instruments produces flat intonation among singers. This possible phenomenon should be studied scientifically. At the same time, it would be ponderable to study the intonation by singers above the harmony performed in equal temperament and harmony performed in just intonation. Pop music harmonies are often very simple. It would be rather simple to apply a maximally pure tuned temperament to them. To develop this research subject further, it could be expanding to find out, what kind of reactions and preferences maximally pure tuned harmony assembled to pop music or even jazz music can cause among listeners.

Equally tempered pianos are important tools of choir directors around the Western world. There are a plenty of easy ways to assemble different temperaments to electric keyboards. The influence of pure tuned triads to the intonation by choir or ensemble could be a worth of studying.

There is solo repertoire in string instrument literature in which couple, triple and quadrable stops are used. The intonation of these chords is often, if I may say, fuzzy. The simple analysis on the basis of just intonation and methods of dealing with the syntonic comma could help many instrumentalists. It would be possible to create an “intonation group” and an “ordinary” group of players. Then the intonation would be measured and compared.

Speaking of string instruments, the intonation by string quartet would be a worth exploring. In ordinary observations, it seems that string quartets often make practical solutions of intonation at basis of melodic intonation. This, as previous findings have shown, often leads to Pythagorean ratios of intervals. Vertical chords sound tensioned and stretched. The research design where a professional string quartet would be a “student of just intonation.” A kind of “beat elimination” (Miles, 1972) but through the intonation analysis marked into sheet of music and professional instructions. I am an optimist in respect of improving the sound and intonation by string ensembles! This article could be titled as “The misconception of sharp intonation—Don’t be afraid of flat Intonation in thirds and sixths.”

Harmonies used in popular music can locally be stereotypical and simple compared with harmonies of contemporary concert music. Sometimes these harmonies can be a certain kind of simplifications of canonical Western harmony. It is completely possible that there are three to four chords used in one piece, probably from diatonic scale. If one examines the evolution of intonation and tuning through the centuries, it is easy to notice the principle according to which more solutions to tuning discrepancies had to be found because of harmony became more and more complex. Chromatic harmony in late Romantic period simply requires equal tempering to be able to be played with acceptable tuning errors and with keyboard with 12 tones per octave. Instead, just intonation intervals can be used in certain simple harmony of 16th century Renaissance period. The music of baroque and classicism needs a plenty of tempering, but not equal tempering. In choir music a cappella, there are excerpts of compositions, where just intonation is possible. But also, complex harmonic turns which absolutely needs tempering if pitch drift is denied. So, it is completely absurd that pop-industry uses equal temperament in maximally simple pop harmonies. The simplest pop songs could be performed in just intonation or in some kind of extended just intonation. Of course, there would be adjustment issues with electric guitar and bass instruments, but this huge potential should not be lost as now happens. Dozens of old keyboard temperaments from meantone tuning to Neidhardt temperaments would be more than suitable to most typical pop music harmonies. This is a massive gap in research of intonation issues.

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Appendices

Appendix 1. The questionnaire and aural instructions of Experiment 1

EPÄPUHTAUKSIEN HAVAITSEMINEN / ENSIMMÄISEN TESTIN SOINTUSARJAT

Taustatiedot

Rastita oikea vaihtoehto.

Mikä on pääinstrumenttisi?

a) jousisoitin	___
b) vaskipuhallin	___
c) puupuhallin	___
d) piano, kantele, kitara harppu tai lyömäsoittimet	___

Olen soittanut pääinstrumenttiani ___ vuotta

Mitä ääntä laulat kuorossa?

1. ääntä ___
2. ääntä ___
3. ääntä ___

Olen poika ___

Olen tyttö ___

Ikäni on ___vuotta

Kuulet 40 sointusarjaa, joissa kaikissa on seitsemän sointua. Ensimmäiset kaksi sointua ovat kestoltaan puolinuotteja, soinnut 3–6 ovat kestoltaan neljäsosanuotteja ja viimeinen sointu on kokonuotti. Tempo on 52 neljäsosanuottia minuutissa.

Sinun tehtäväsi on kuunnella jokaisesta sointusarjasta **kolmatta**, **neljättä**, **viidettä** ja **kuudetta** sointua, siis neljäsosanuotin mittaisia nuotteja. Merkitse rastilla lomakkeelle, mikä näistä neljästä soinnusta kuulostaa mielestäsi epäpuhtaimmalta, epävireisimmältä, ”falskeimmalta” kussakin sointusarjassa. Älä kiinnitä huomiota harmonian luontevuuteen, vaan yksittäisten sointujen puhtauteen. Jokainen sointusarja soitetaan kahdesti.

Ennen kuin varsinainen testi alkaa, kuulet lyhennelmän yllä olevasta tekstistä kuulokkeistasi. Sen jälkeen kuulet yhden esimerkkisointusarjan. Sekin soitetaan kahdesti. Sinun ei tarvitse merkitä mitään lomakkeeseen siinä vaiheessa. Sen jälkeen kuulet lauseen ”testi alkaa” ja heti perään ”näyte 1”. Testin alettua kuulet sointusarjat kahdesti soitettuna. Jokaisen näytteen välissä kerrotaan seuraavan näytteen numero. Näin jatketaan testin loppuun saakka. Tervetuloa testiin!

Näyte	sointu 1	sointu 2	sointu 3	sointu 4	sointu 5	sointu 6	sointu 7
näyte 1	******	******					******
näyte 2	******	******					******
näyte 3	******	******					******
näyte 4	******	******					******
näyte 5	******	******					******
näyte 6	******	******					******
näyte 7	******	******					******
näyte 8	******	******					******
näyte 9	******	******					******
näyte 10	******	******					******
näyte 11	******	******					******
näyte 12	******	******					******
näyte 13	******	******					******
näyte 14	******	******					******
näyte 15	******	******					******
näyte 16	******	******					******
näyte 17	******	******					******
näyte 18	******	******					******
näyte 19	******	******					******
näyte 20	******	******					******
näyte 21	******	******					******
näyte 22	******	******					******
näyte 23	******	******					******
näyte 24	******	******					******
näyte 25	******	******					******
näyte 26	******	******					******
näyte 27	******	******					******
näyte 28	******	******					******
näyte 29	******	******					******
näyte 30	******	******					******
näyte 31	******	******					******
näyte 32	******	******					******
näyte 33	******	******					******
näyte 34	******	******					******
näyte 35	******	******					******
näyte 36	******	******					******
näyte 37	******	******					******

näyte 38	******	******					******
näyte 39	******	******					******
näyte 40	******	******					******

RECOGNITION OF MISTUNED CHORDS EXPERIMENT 1

Background information

Please cross the correct alternative:

I am

a) a string instrument player ___
b) a wind instrument player ___
c) a keyboard or percussion player ___
d) a singer ___

I have experienced my main instrument ___ years

Please draw a circle on one of the following alternatives which describes you as a music listener. During my leisure time I prefer listen mainly to

a) Western art music and choral music acoustically produced. I visit concerts.
b) all kinds of channels from radio, widely, how it happens. Sometimes I visit concerts.
c) different kind of music than at my work. I do not visit concerts very much during my leisure time. I prefer to listen electrically produced pop-music with headphones or ear buds.
d) silence. I hear enough music at my work, I hardly do not listen to music during my leasure time.

I am a male ___
I am a female ___
My age is ___ years

You will hear 40 chord progressions. There are seven chords in every chord progression. The first two chords are half notes in duration. The chords 3-6 are quarter notes. The last chord is whole note. The tempo is 52 quarter notes per minute.

Listen to very carefully the **third**, the **fourth**, the **fifth**, and the **sixth** chord of every chord progression, thus quarter notes. Please write down to the answering form, which of these four chords sounds the most **mistuned**, **out-of-tune**, **false**. Please do not pay attention to the naturality of chords but only the purity of single chords. Every chord progression is played twice.

Before the actual test begins, you will hear the abstract of this text in spoken in your headphones. After this, you will hear the example of chord progression. It is played twice, too. You do not have to write anything to you answering form. After this, you will hear the sentence “The test begins” and “sample 1”. When the test has begun, the samples are played twice. Between samples you will hear the number of the next sample. This is the way how this test works until the end. Welcome to the test!

Sample	chord 1	chord 2	chord 3	chord 4	chord 5	chord 6	chord 7
sample 1	******	******					******
sample 2	******	******					******
sample 3	******	******					******
sample 4	******	******					******
sample 5	******	******					******
sample 6	******	******					******
sample 7	******	******					******
sample 8	******	******					******
sample 9	******	******					******
sample 10	******	******					******
sample 11	******	******					******
sample 12	******	******					******
sample 13	******	******					******
sample 14	******	******					******
sample 15	******	******					******
sample 16	******	******					******
sample 17	******	******					******
sample 18	******	******					******
sample 19	******	******					******
sample 20	******	******					******
sample 21	******	******					******
sample 22	******	******					******
sample 23	******	******					******
sample 24	******	******					******
sample 25	******	******					******

sample 26	******	******					******
sample 27	******	******					******
sample 28	******	******					******
sample 29	******	******					******
sample 30	******	******					******
sample 31	******	******					******
sample 32	******	******					******
sample 33	******	******					******
sample 34	******	******					******
sample 35	******	******					******
sample 36	******	******					******
sample 37	******	******					******
sample 38	******	******					******
sample 39	******	******					******
sample 40	******	******					******

Appendix 2. The approval form for parents of the underaged participants of Experiment 1

ARVOISA MUSIIKKILUOKKALAISEN OPPILAAN HUOLTAJA

Olen tekemässä musiikkikasvatuksen alaan kuuluvaa väitöskirjatutkimusta, joka käsittelee musiikilliseen intonaatioon liittyvää havaitsemista ja intonaatioon liittyviä mieltymyksiä. Oulun kaupunki on myöntänyt minulle tutkimusluvan 29.1.2015. Olen nyt pyytämässä koehenkilöiksi ala- ja yläkouluikäisiä musiikkiluokkalaisia, ammattiopintojensa alussa olevia instrumenttiopiskelijoita sekä ammattimuusikoita.

Musiikkiluokkaa käyvät oppilaat 5.–9. musiikkiluokalla olisi ihanteellinen osallistujaryhmä. Siksi lähestyn nyt teitä, Teuvo Pakkalan 5. ja 6. musiikkiluokan oppilaiden huoltajat. Pyydän saada tehdä kaksi musiikkipsykologista koetta näiden kahden luokan oppilaille.

Ensimmäisessä kokeessa tutkitaan sävelpuhtauteen liittyvää havaitsemista 40 sointusarjalla. Koe kestää noin puoli tuntia. Toisessa kokeessa tutkitaan osallistujien intonaatiomieltymyksiä 30 sointusarjaparilla. Tämä koe kestää noin 45 min. On siis kyse kvantitatiivisista musiikkipsykologisista tutkimusasetelmista.

Oppilaille soitetaan kuulokkeiden kautta digitaalisesti tehtyjä sointusarjoja, joissa on erilaisia sävelpuhtausmuutoksia mukana. Yksi sointusarja kestää n. 10 sekuntia. Sointusarjojen välissä on taukoja. Sointusarjojen esittämisen voimakkuus ei aiheuta haittaa kuuloelimille. Kokeen voi keskeyttää, jos oppilas niin haluaa. Koe ei aiheuta psyykkistä haittaa osallistujille.

Yliopiston tohtoriopiskelijat suorittavat Tieteellinen tutkimus ja etiikka -kurssin. Tutkimuksessa noudatetaan yliopiston hyväksymiä käytäntöjä: http://www.oulu.fi/hutk/node/10238.

Pidän kokeet Teuvo Pakkalan koululla. Kaikki kokeet pidetään koulupäivän aikana ja luokan oma opettaja on mukana molemmissa tilaisuudessa ja vastaa siirtymisistä koululta tutkimuspaikalle ja takaisin.

Kokeet pidetään seuraavina ajankohtina
xx.xx.2015 klo XX
xx.xx.2015 klo XX

PALAUTA TÄMÄ OSA OPETTAJALLE

LAPSENI ______________________________________

VOI OSALLISTUA KOKEISIIN ___

EI VOI OSALLISTUA KOKEISIIN ___

Annan mielelläni lisätietoja tarvittaessa.

Oulussa 5. maaliskuuta 2015

t.
Markku Viitasaari
FL, KM, LO, MO, musiikkipedagogi
tohtoriopiskelija / Oulun yliopiston tutkijakoulu
050 3444886
mviitasa@student.oulu.fi

Appendix 3. The approval form of Experiment 2

INTONAATIOMIELTYMYKSET / TOISEN TESTIN SOINTUSARJAT

Rastita oikea vaihtoehto.
Mikä on pääinstrumenttisi?
jousisoitin ___
vaskipuhallin ___
puupuhallin ___
piano, kantele, kitara, harppu tai lyömäsoittimet ___

Olen soittanut pääinstrumenttiani ___ vuotta

Musiikillinen tausta (ympyröi se vaihtoehto, joka parhaiten kuvaa musiikillista taustaasi ennen musiikin yliopisto-opintojasi).

Musiikkiluokkatausta
  - musiikkiluokalla vähintään alakoulussa
  - musiikkilukio/musiikkiopisto
  - kuorossa laulaminen mukana koko ajan

Musiikkiopistotausta
  - vähintään perustason oppimäärä suoritettu tai musiikkiopistotason oppimäärä
  - klassinen musiikki, instrumenttiopetus
  - ei juuri kokemusta nk. “kevyestä” musiikista, ei kuoroharrastusta

Bänditausta
  - pop, rock, jazz
  - bändisoitinten soittoa, ehkä useampia
  - omia bändejä
  - ei muodollisia musiikkiopintoja / vähän muodollisia opintoja

Kansanmusiikkitausta
  - pelimannitraditio, kansanmusiikkiyhtyeet
  - kiinnostus etnisiin musiikkikulttuureihin, myös perehtymistä niihin

Jos haluat tarkentaa sinua parhaiten kuvaavaa vaihtoehtoa, kirjoita tähän.

Olen mies ___ nainen ___
Ikäni on ___ vuotta

Appendix 4. Aural instructions and response packet of Experiment 2

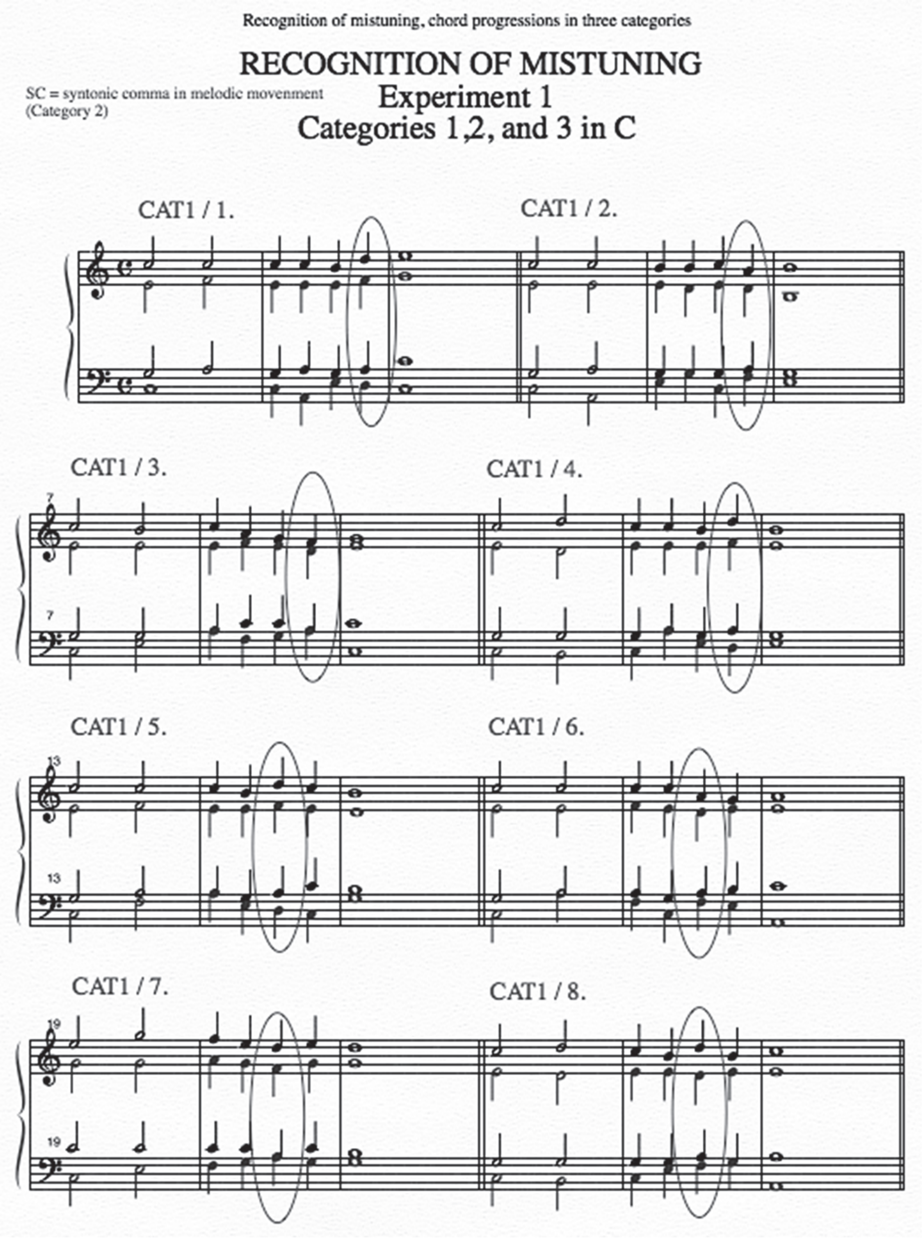
Kuulet 30 sointusarjaa, joissa kaikissa on seitsemän sointua. Ensimmäiset kaksi sointua ovat kestoltaan puolinuotteja, soinnut 3–6 ovat kestoltaan neljäsosanuotteja ja viimeinen sointu on kokonuotti. Tempo on 52 neljäsosanuottia minuutissa. Jokainen sointusarja soitetaan kahdella eri virityksellä. Sinun tehtäväsi on kirjoittaa lomakkeen kääntöpuolelle, kumpi sointusarjan virityksistä miellyttää sinua enemmän, kummasta siis pidät enemmän ja kumpaa pidät toista paremmin soivana virityksenä. Testissä käytetään useita virityksiä ja ne ovat satunnaisessa järjestyksessä.

Ennen kuin varsinainen testi alkaa, kuulet yhden esimerkin sointusarjoista. Sinun ei tarvitse merkitä mitään lomakkeeseen siinä vaiheessa. Sen jälkeen kuulet lauseen “testi alkaa” ja heti perään “ensimmäinen näyte”. Jokaisen sointusarjaparin jälkeen on pieni tauko, jonka aikana kerrotaan seuraavan sointusarjaparin numero. Näin jatketaan testin loppuun saakka. Tervetuloa testiin!

Parit	Ensimmäinen sointusarja	Toinen sointusarja
1. pari		
2. pari		
3. pari		
4. pari		
5. pari		
6. pari		
7. pari		
8. pari		
9. pari		
10. pari		
11. pari		
12. pari		
13. pari		
14. pari		
15. pari		
16. pari		
17. pari		
18. pari		
19. pari		
20. pari		
21. pari		
22. pari		

23. pari		
24. pari		
25. pari		
26. pari		
27. pari		
28. pari		
29. pari		
30. pari		

Appendix 5. Experiment 1: Chord progressions by categories in C



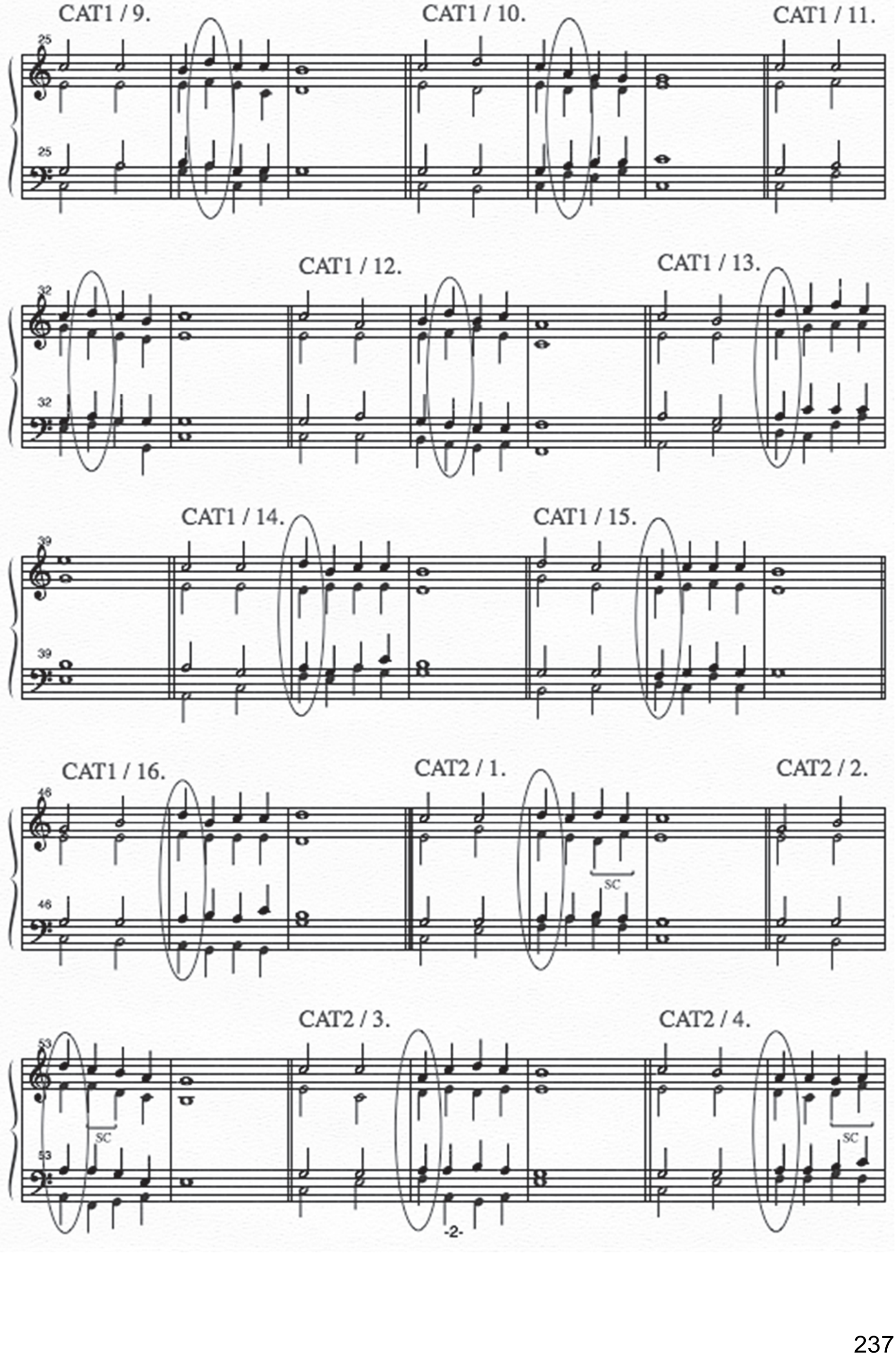
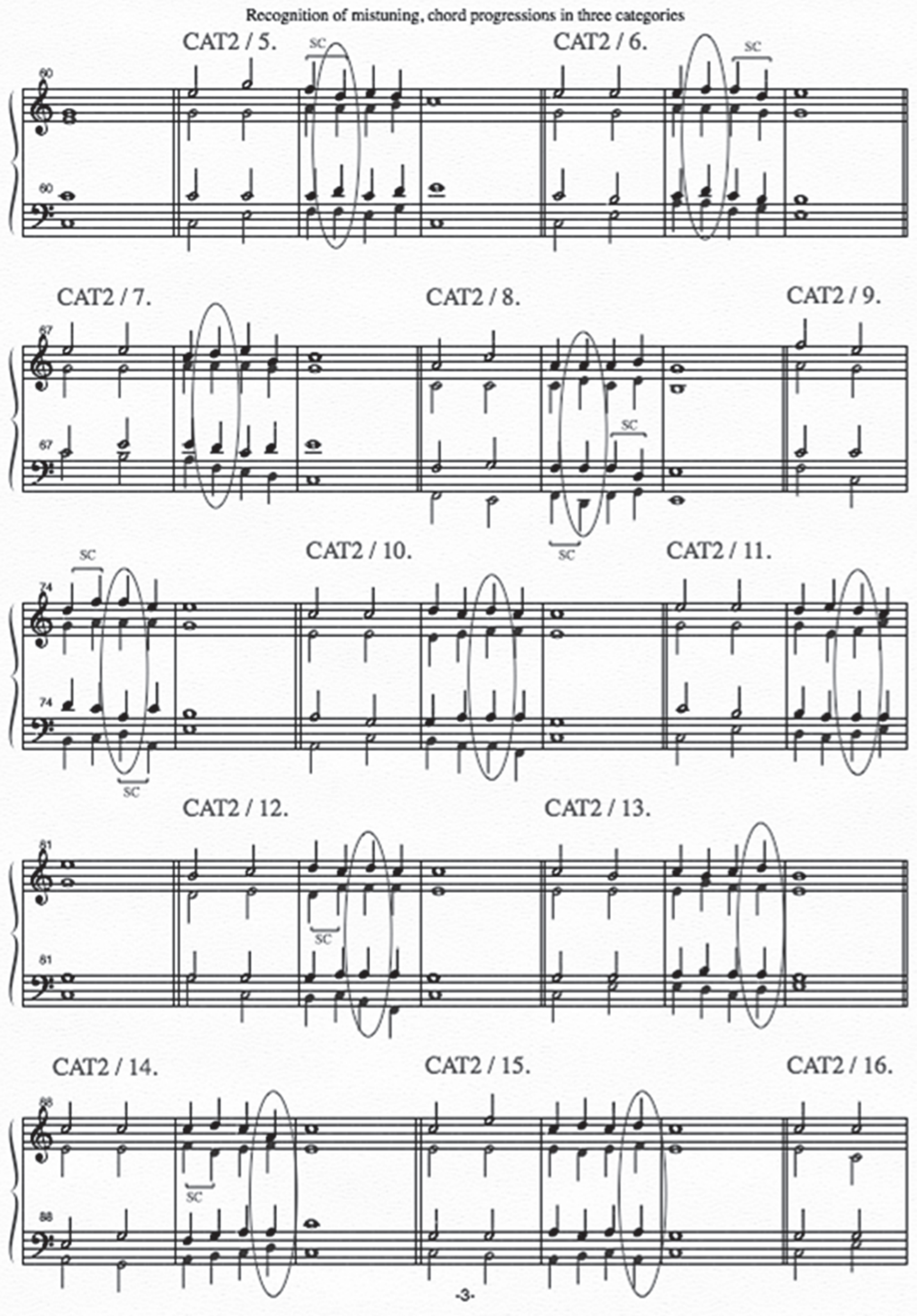
Recognition of mistuning, chord progressions in three categories

RECOGNITION OF MISTUNING

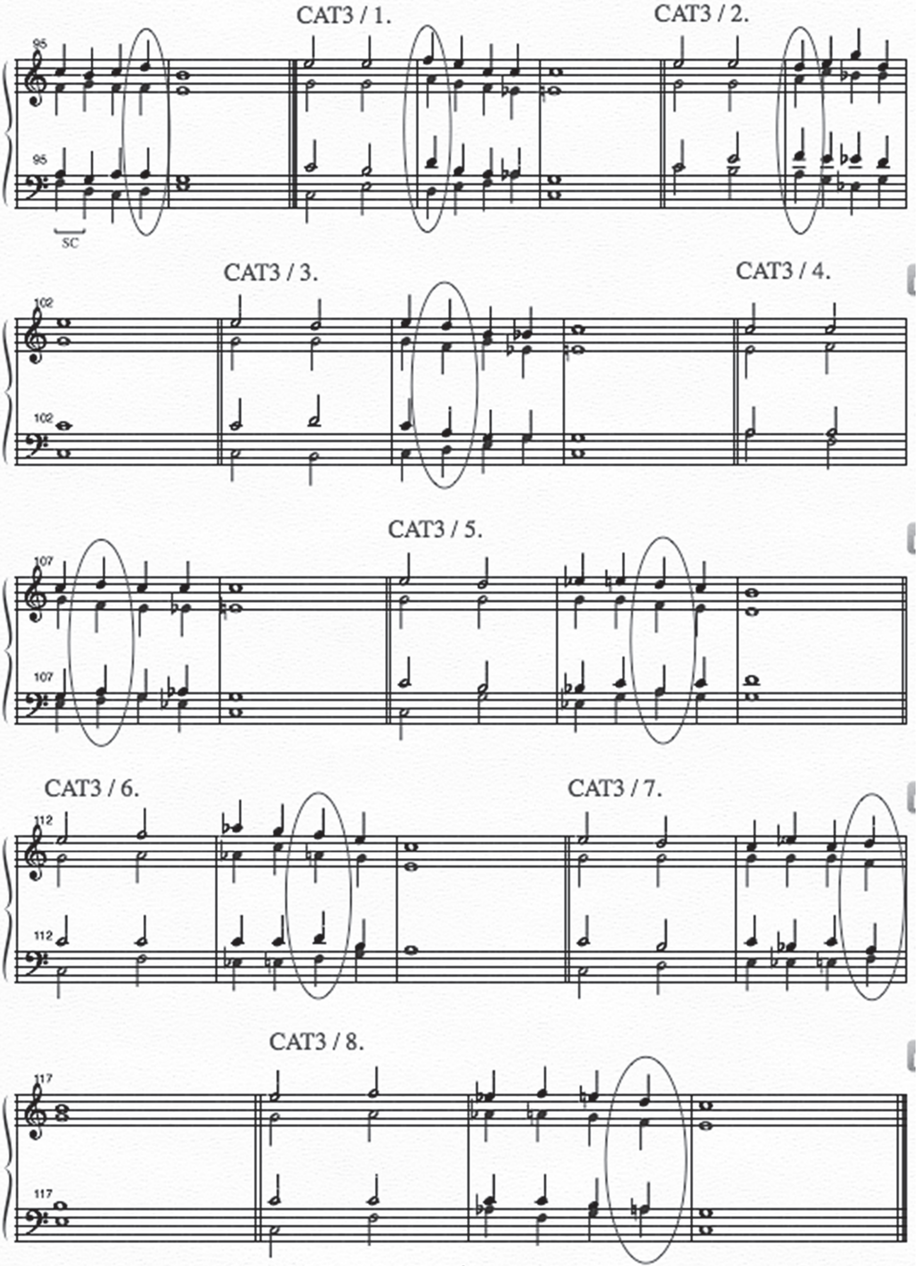
SC = syntonic comma in melodic movement
(Category 2)

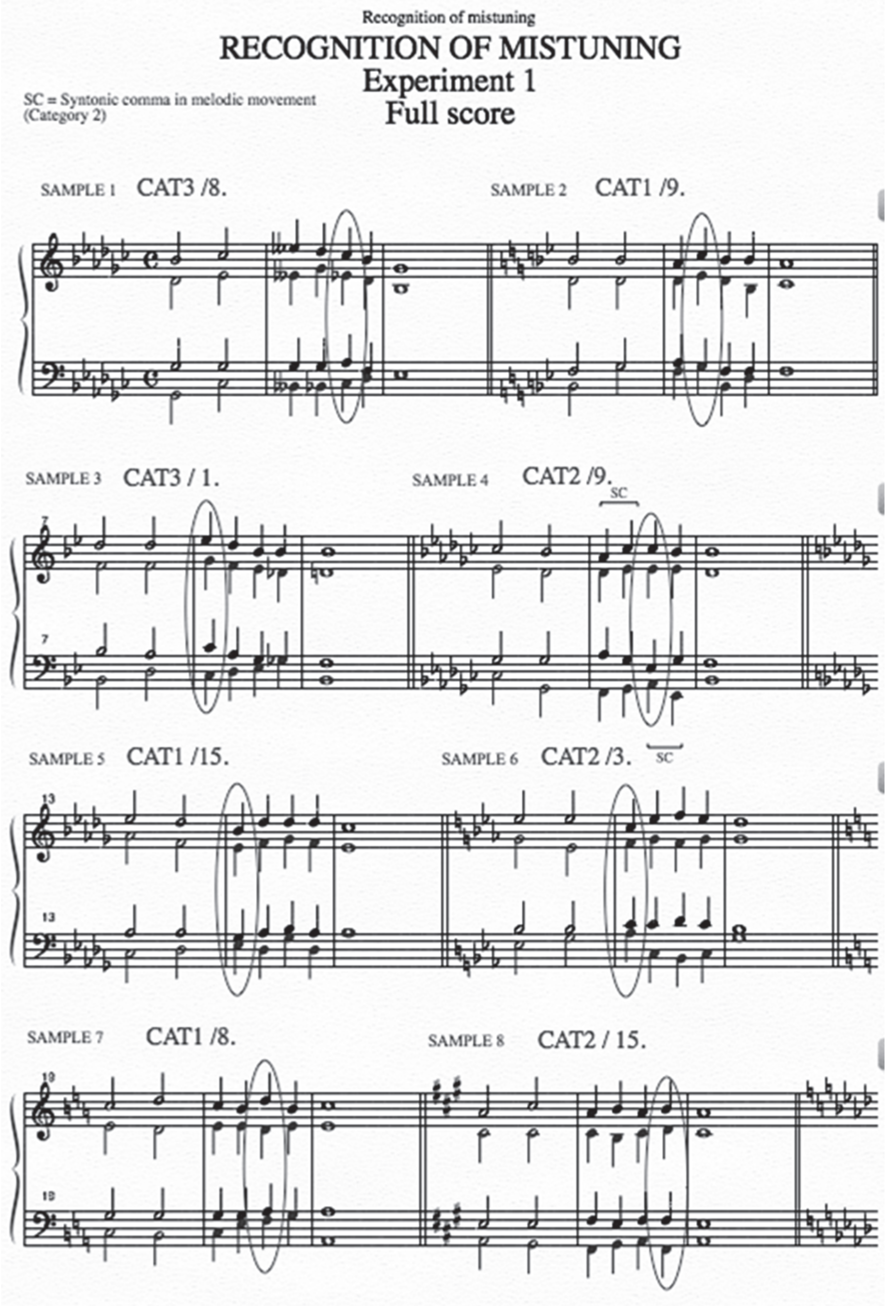
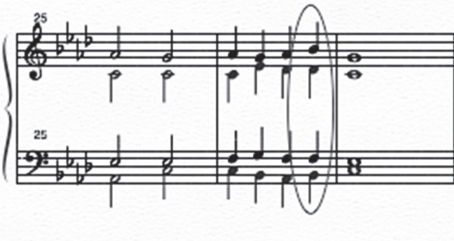
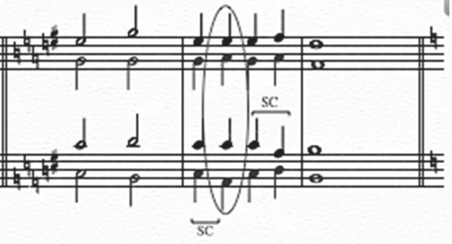
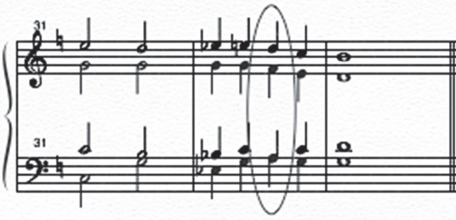
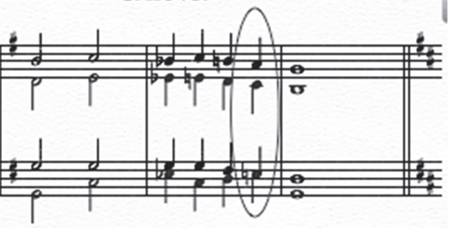
Experiment 1

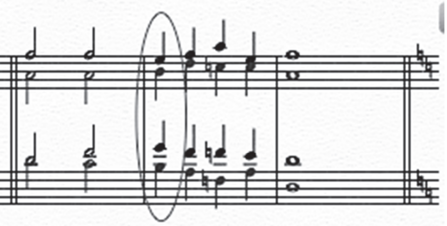
Categories 1,2, and 3 in C

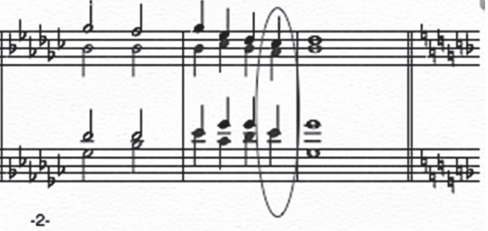
Recognition of mistuning, chord progressions in three categories


Recognition of mistuning, chord progressions in three categories

Recognition of mistuning, chord progressions in three categories

-4-

Appendix 6. Experiment 1: The full score of Experiment 1

SAMPLE 9 CAT2 / 13.

SAMPLE 10 CAT2 /8.

SAMPLE 11 CAT3 / 5.

SAMPLE 12 CAT3 /8.

SAMPLE 13 CAT2 /1.

SAMPLE 14 CAT3 / 2.

SAMPLE 15 CAT1 /1.

SAMPLE 16 CAT1 /3.

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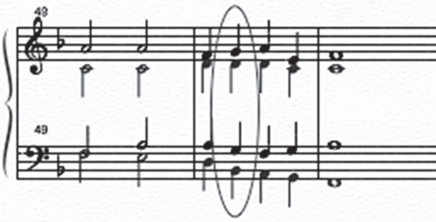
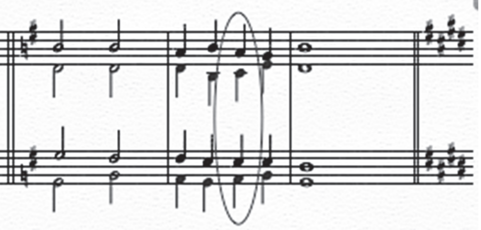

SAMPLE 18 **CAT2 / 11.**



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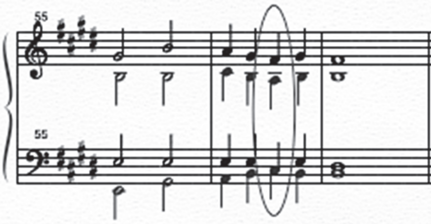
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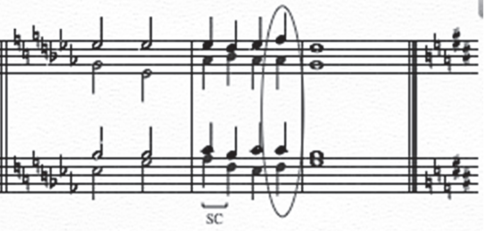
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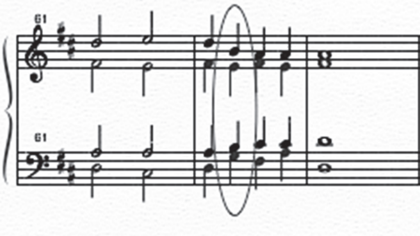
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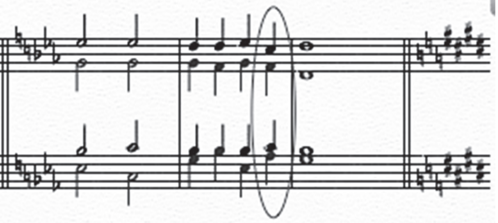
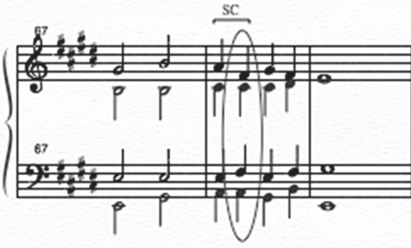
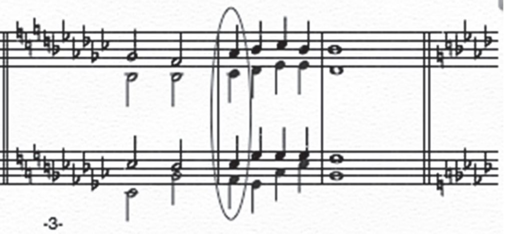

SAMPLE 23 **CAT2 /5.**



SAMPLE 24 **CAT1 /13.**

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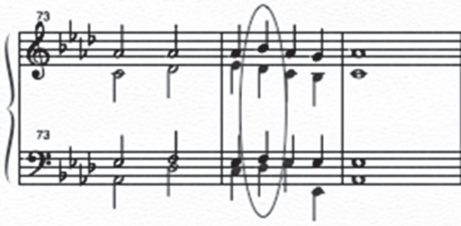
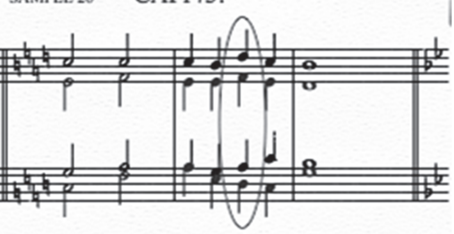

SAMPLE 26 **CAT1 /5.**



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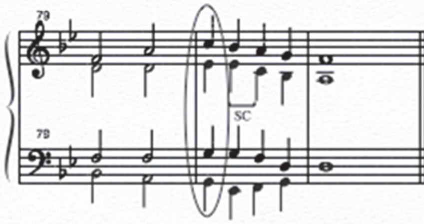
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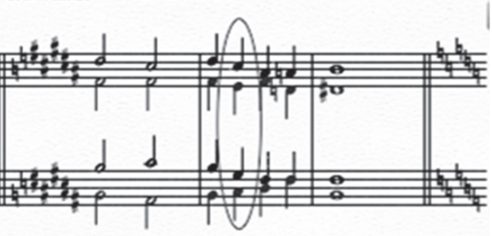
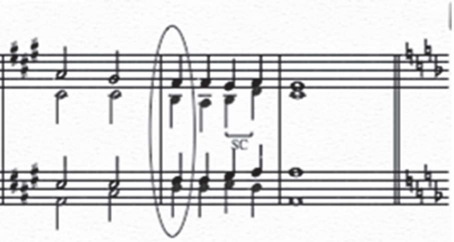
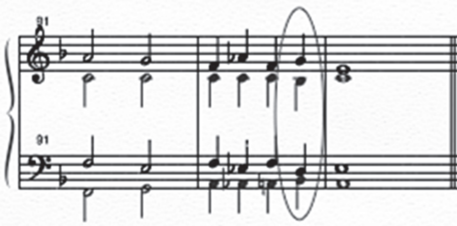
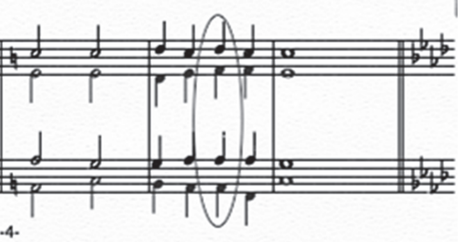
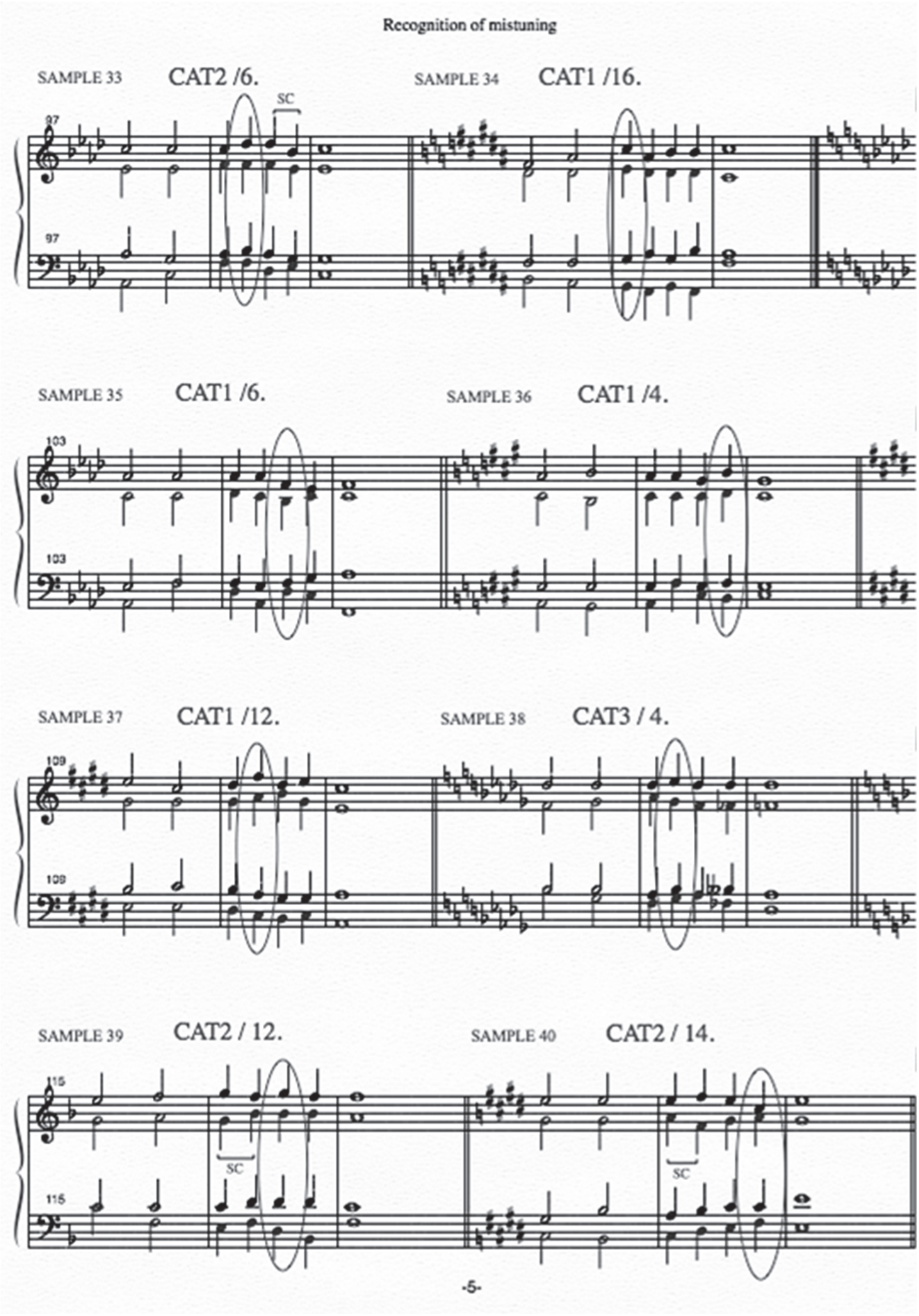

SAMPLE 29 **CAT1 /14.**

SAMPLE 30 **CAT2 /4.**

SAMPLE 31 **CAT3 /7.**

SAMPLE 32 **CAT2 /10.**



Recognition of mistuning

SAMPLE 33 CAT2 /6.

SAMPLE 34 CAT1 /16.

SAMPLE 35 CAT1 /6.

SAMPLE 36 CAT1 /4.

SAMPLE 37 CAT1 /12.

SAMPLE 38 CAT3 / 4.

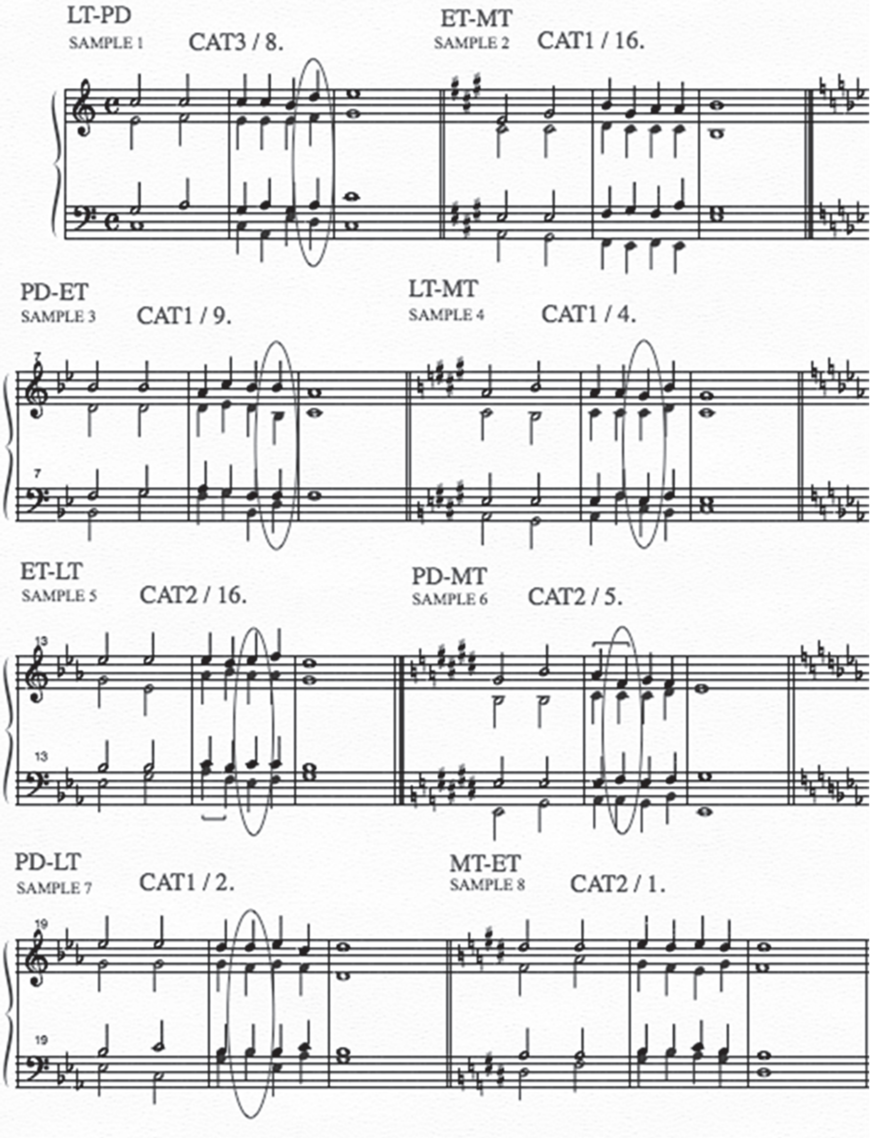
SAMPLE 39 CAT2 / 12.

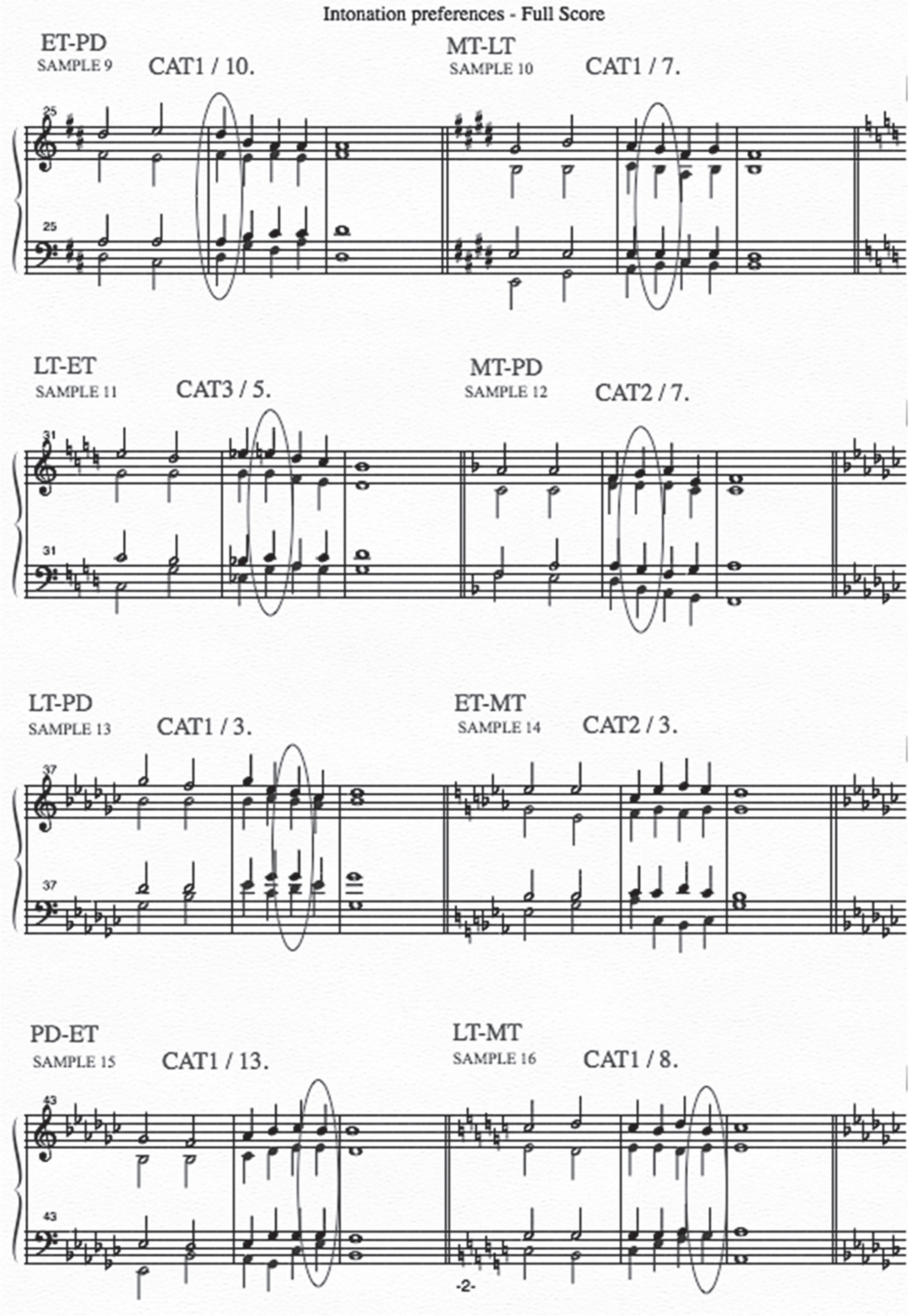
SAMPLE 40 CAT2 / 14.

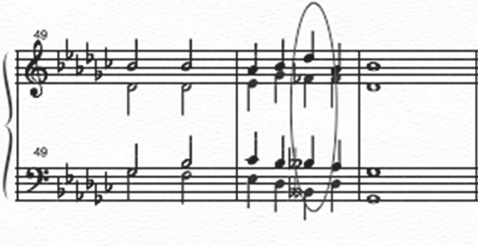
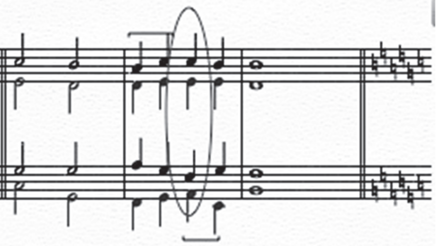
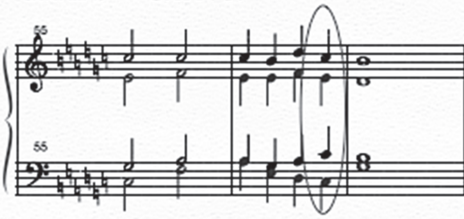
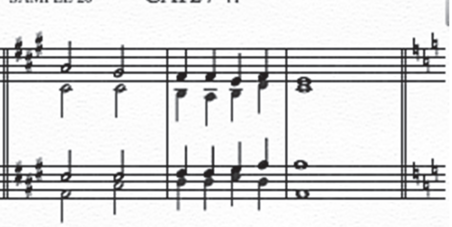
-5-

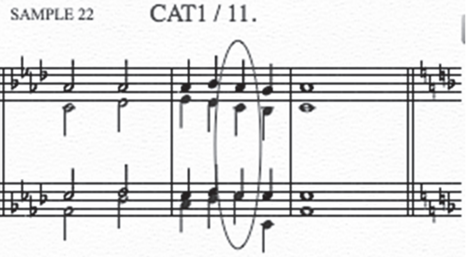
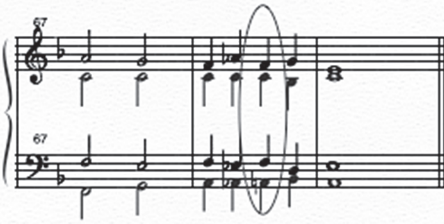
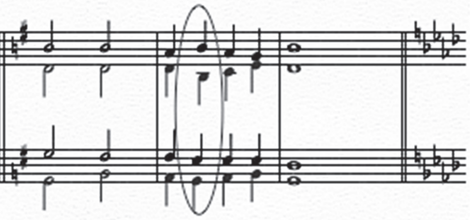
Appendix 7. The full score of Experiment 2

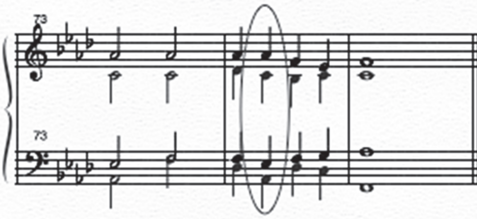
Intonation preferences
30 chord progressions - Full Score

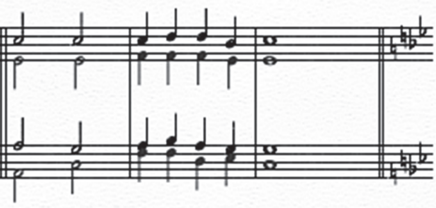


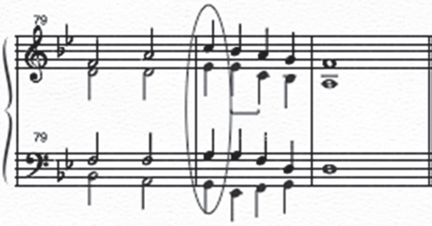

Intonation preferences - Full Score
ET-PD
SAMPLE 9
CAT1 / 10.
MT-LT
SAMPLE 10
CAT1 / 7.
25
25
LT-ET
SAMPLE 11
CAT3 / 5.
MT-PD
SAMPLE 12
CAT2 / 7.
31
31
LT-PD
SAMPLE 13
CAT1 / 3.
ET-MT
SAMPLE 14
CAT2 / 3.
37
37
PD-ET
SAMPLE 15
CAT1 / 13.
LT-MT
SAMPLE 16
CAT1 / 8.
43
43
-2-

ET-LT
SAMPLE 17 CAT3 / 2.

PD-MT
SAMPLE 18 CAT2 / 9.

PD-LT
SAMPLE 19 CAT1 / 5.

MT-ET
SAMPLE 20 CAT2 / 4.

ET-PD
SAMPLE 21 CAT1 / 14.

MT-LT
SAMPLE 22 CAT1 / 11.

LT-ET
SAMPLE 23 CAT3 / 7.

MT-PD
SAMPLE 24 CAT2 / 11.

LT-PD

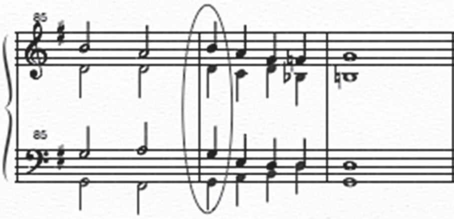
SAMPLE 25 CAT1 / 6.

ET-MT

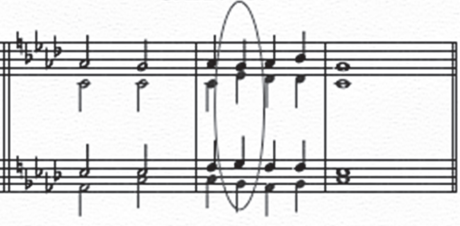
SAMPLE 26 CAT2 / 6.

PD-ET

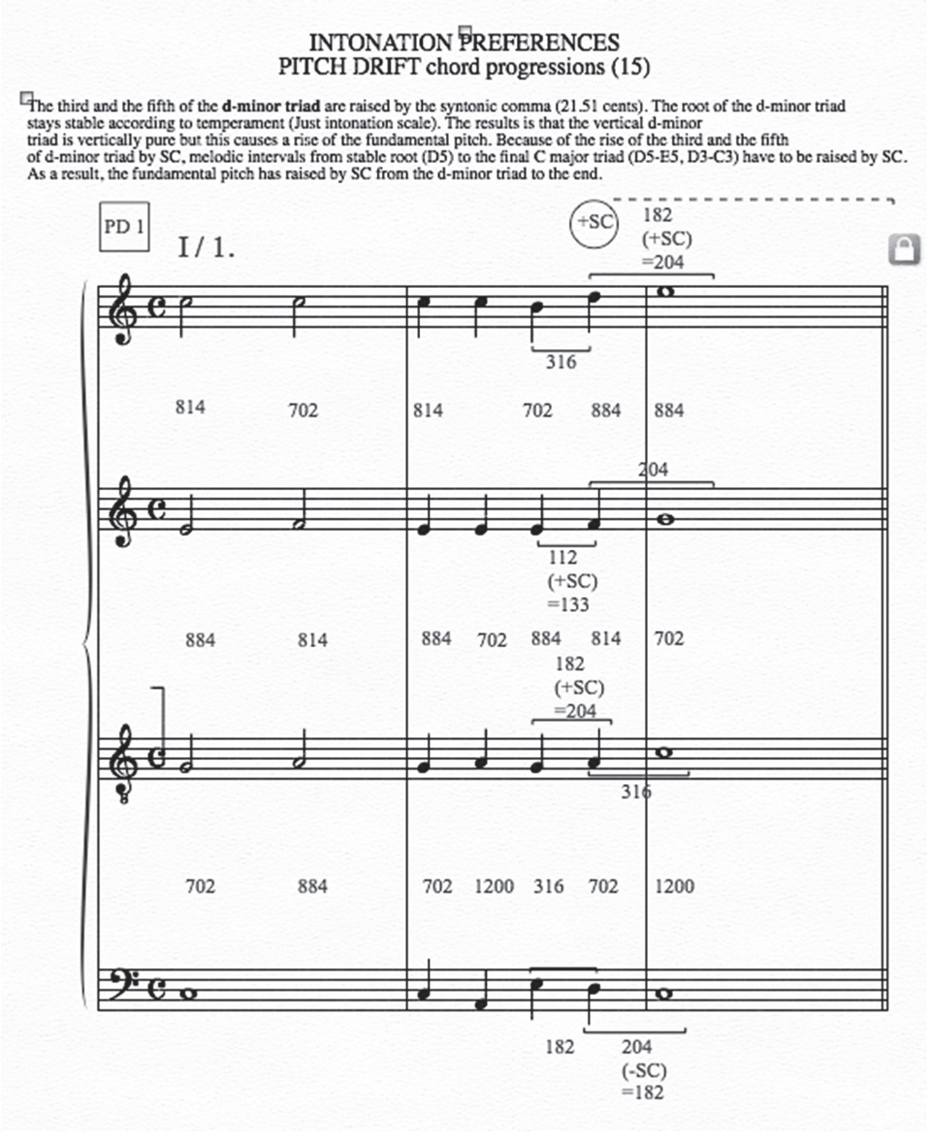
SAMPLE 27 CAT2 / 2.

LT-MT

SAMPLE 28 CAT1 / 12.

ET-LT

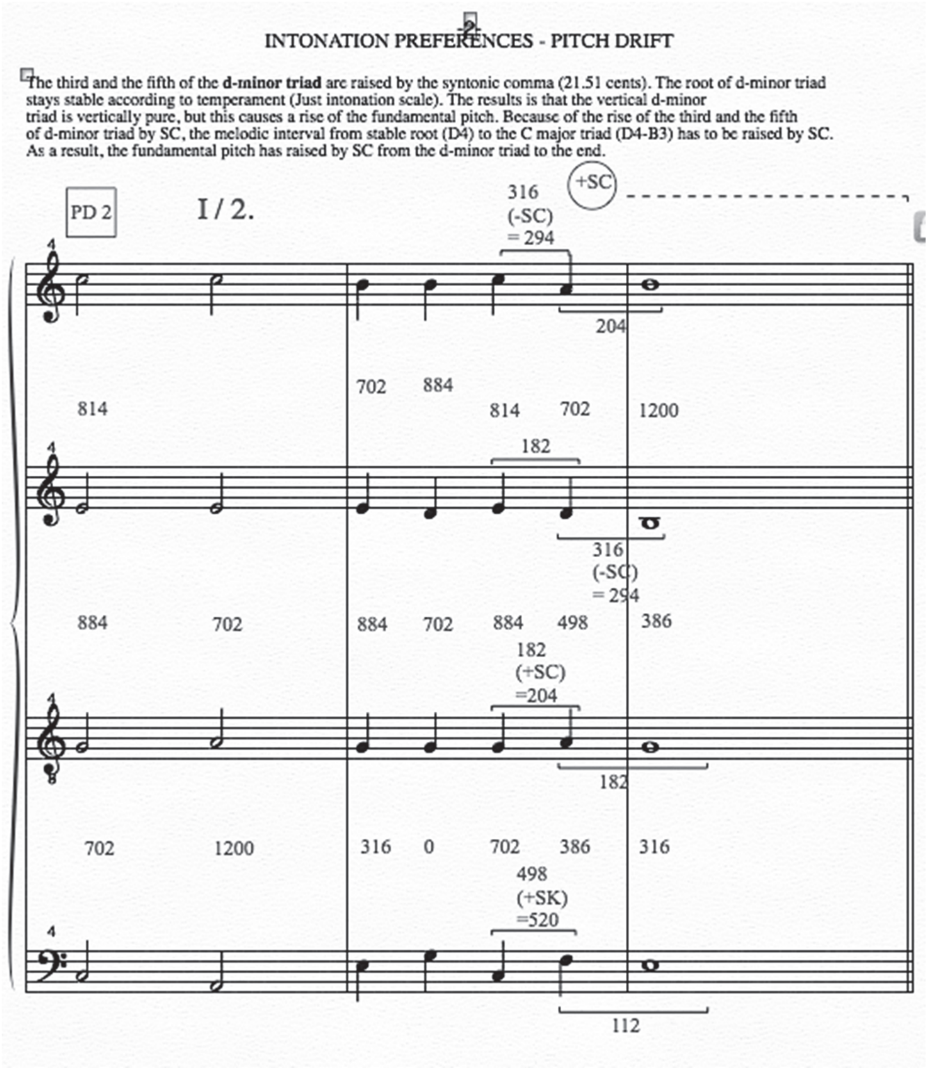
SAMPLE 29 CAT3 / 3.

PD-MT

SAMPLE 30 CAT2 / 13.

Appendix 8. Pitch drift samples



INTONATION PREFERENCES
PITCH DRIFT chord progressions (15)

The third and the fifth of the **d-minor triad** are raised by the syntonic comma (21.51 cents). The root of the d-minor triad stays stable according to temperament (Just intonation scale). The results is that the vertical d-minor triad is vertically pure but this causes a rise of the fundamental pitch. Because of the rise of the third and the fifth of d-minor triad by SC, melodic intervals from stable root (D5) to the final C major triad (D5-E5, D3-C3) have to be raised by SC. As a result, the fundamental pitch has raised by SC from the d-minor triad to the end.

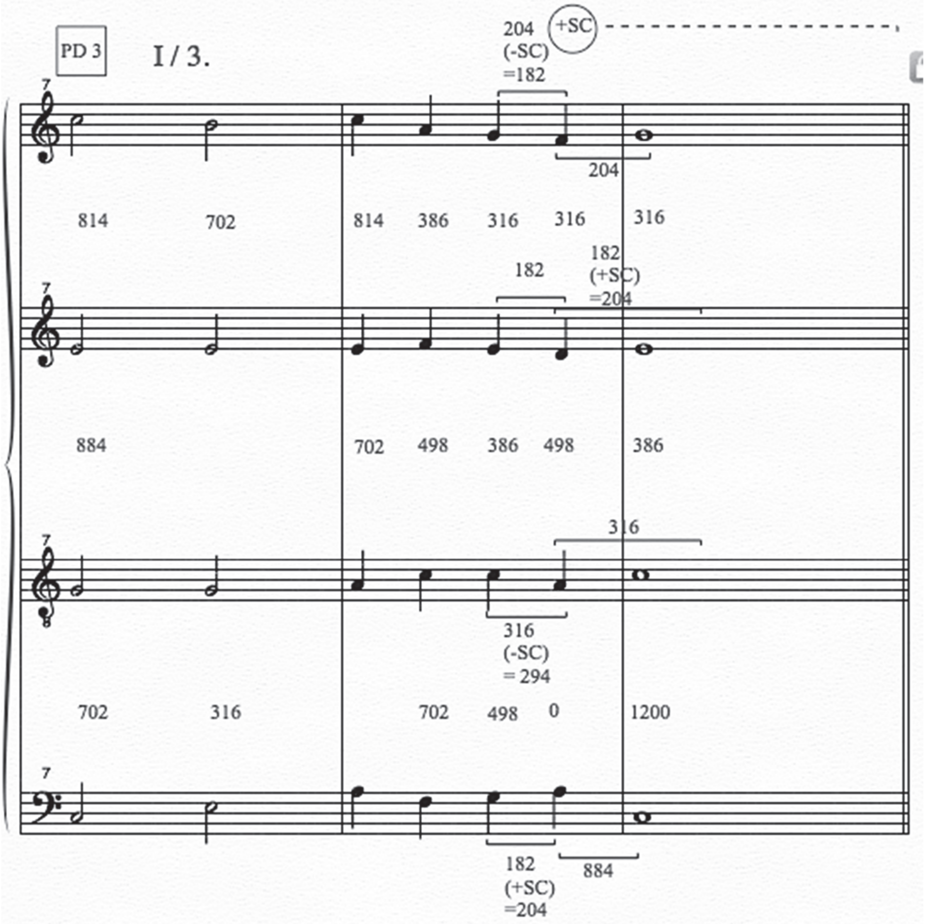


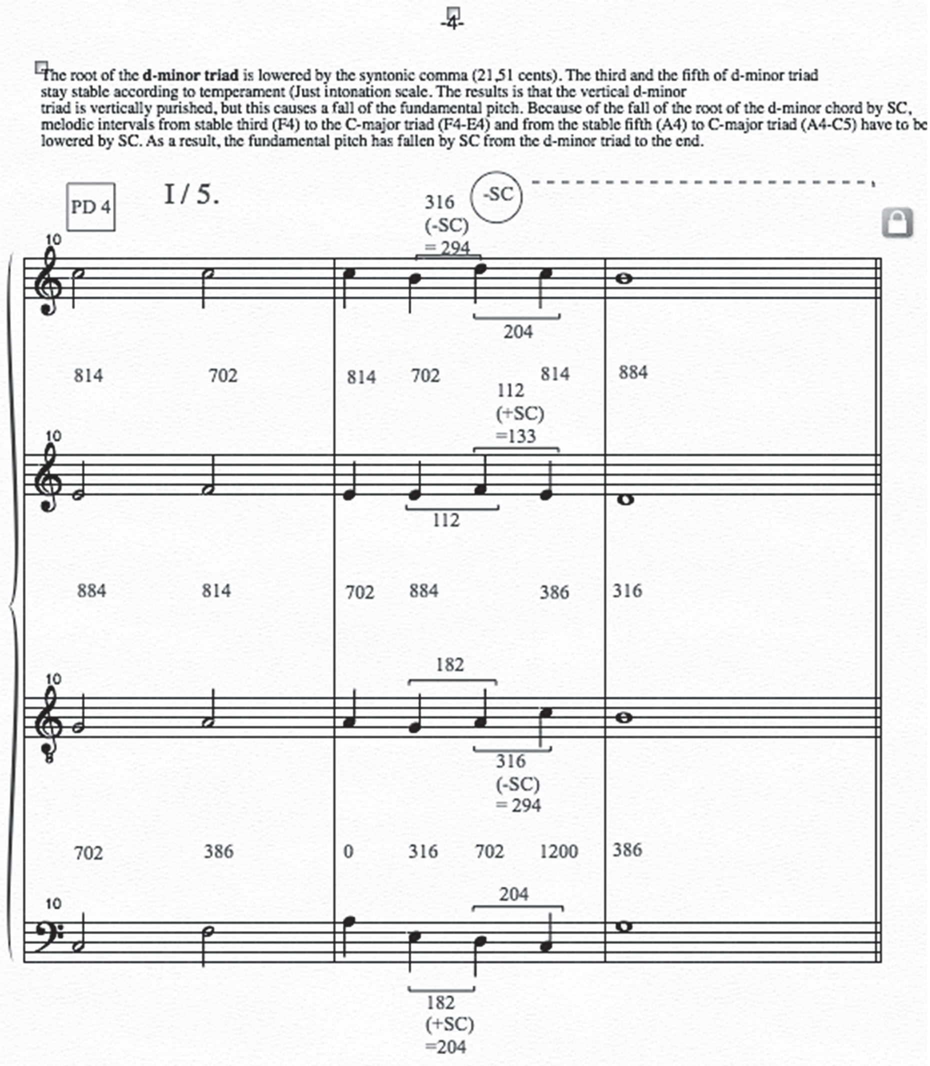
INTONATION PREFERENCES - PITCH DRIFT

The third and the fifth of the **d-minor triad** are raised by the syntonic comma (21.51 cents). The root of d-minor triad stays stable according to temperament (Just intonation scale). The results is that the vertical d-minor triad is vertically pure, but this causes a rise of the fundamental pitch. Because of the rise of the third and the fifth of d-minor triad by SC, the melodic interval from stable root (D4) to the C major triad (D4-B3) has to be raised by SC. As a result, the fundamental pitch has raised by SC from the d-minor triad to the end.

-3-

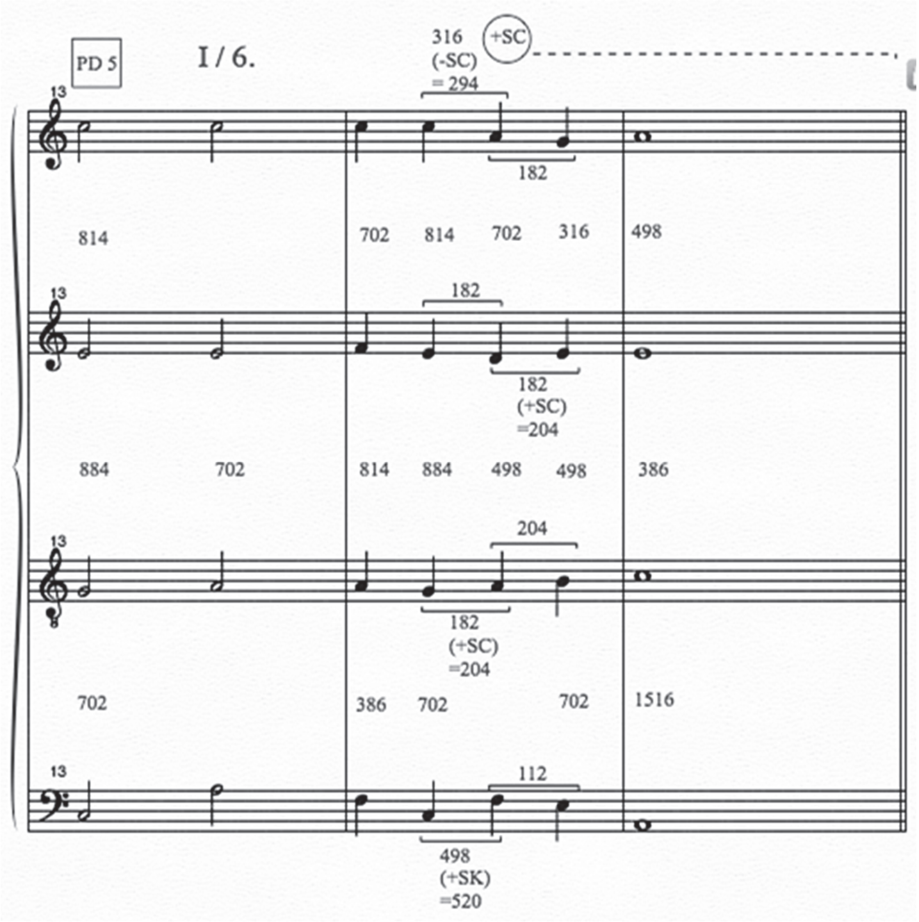
The third and the fifth of the **d-minor triad** are raised by the syntonic comma (21,51 cents). The root of d-minor triad stays stable according to temperament (Just intonation scale). The results is that the vertical d-minor triad is vertically purished, but this causes a rise of the fundamental pitch. Because of the rise of the third and the fifth of d-minor triad by SC, the melodic interval from stable root (D4) to the C-major triad (D4-E4) has to be raised by SC. As a result, the fundamental pitch has raised by SC from the d-minor triad to the end.

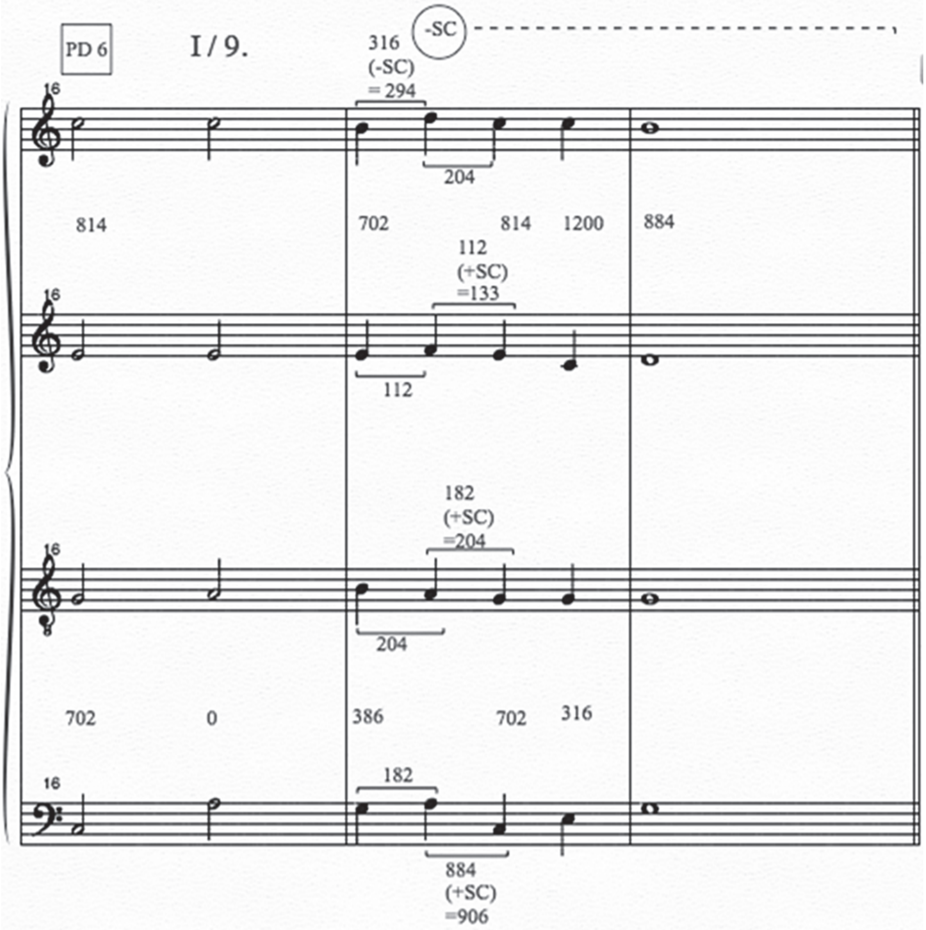


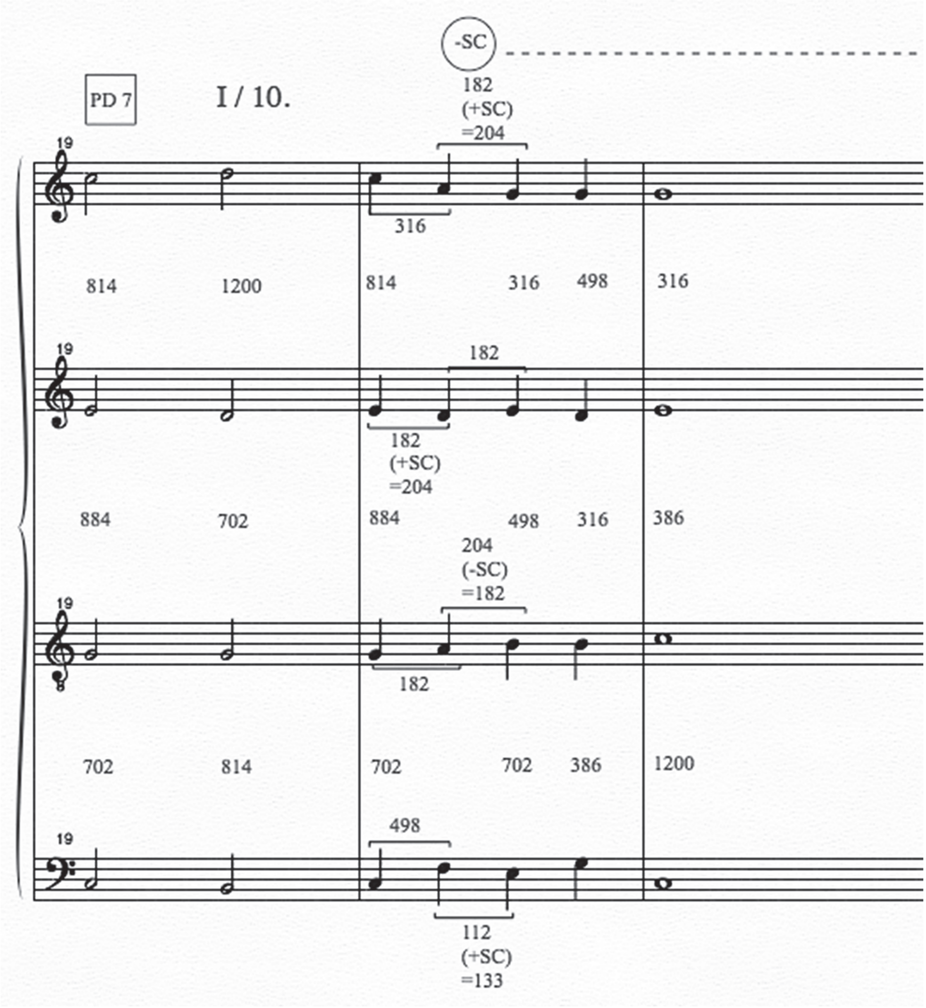


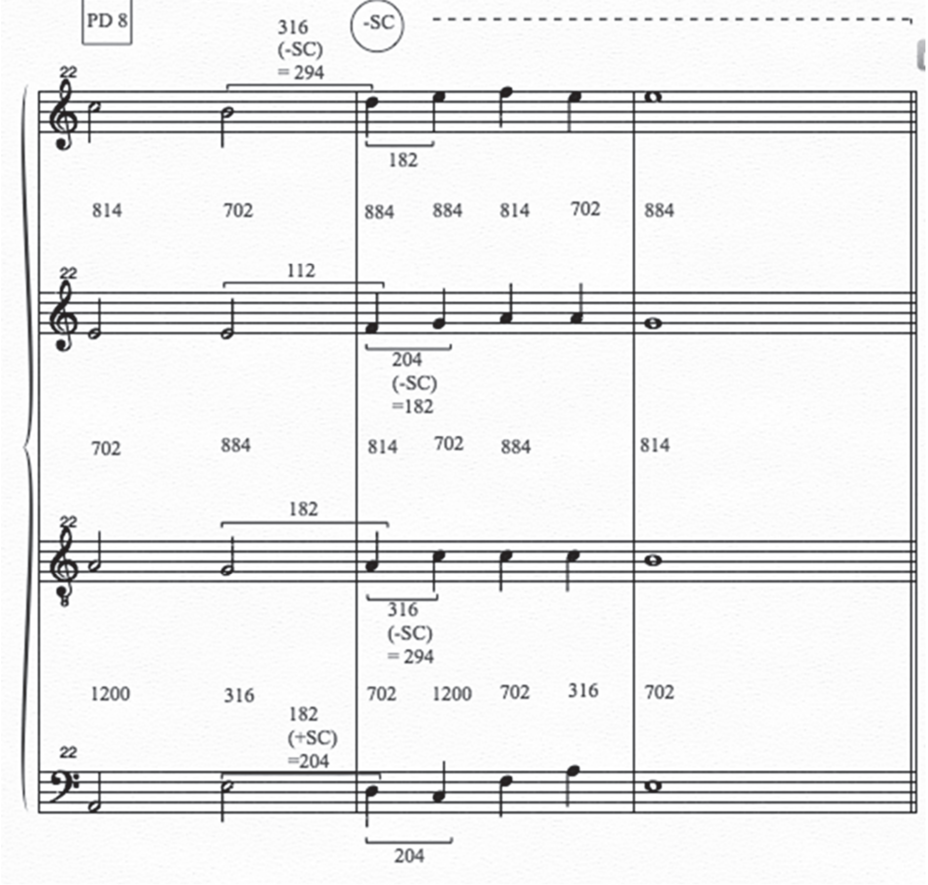
-4-

The root of the **d-minor triad** is lowered by the syntonic comma (21,51 cents). The third and the fifth of d-minor triad stay stable according to temperament (Just intonation scale. The results is that the vertical d-minor triad is vertically purished, but this causes a fall of the fundamental pitch. Because of the fall of the root of the d-minor chord by SC, melodic intervals from stable third (F4) to the C-major triad (F4-E4) and from the stable fifth (A4) to C-major triad (A4-C5) have to be lowered by SC. As a result, the fundamental pitch has fallen by SC from the d-minor triad to the end.


PD 5
I / 6.
316 (-SC) = 294
+SC
13
182
814
702
814
702
316
498
13
182
182 (+SC) =204
884
702
814
884
498
498
386
13
204
182 (+SC) =204
702
386
702
702
1516
13
112
498 (+SK) =520

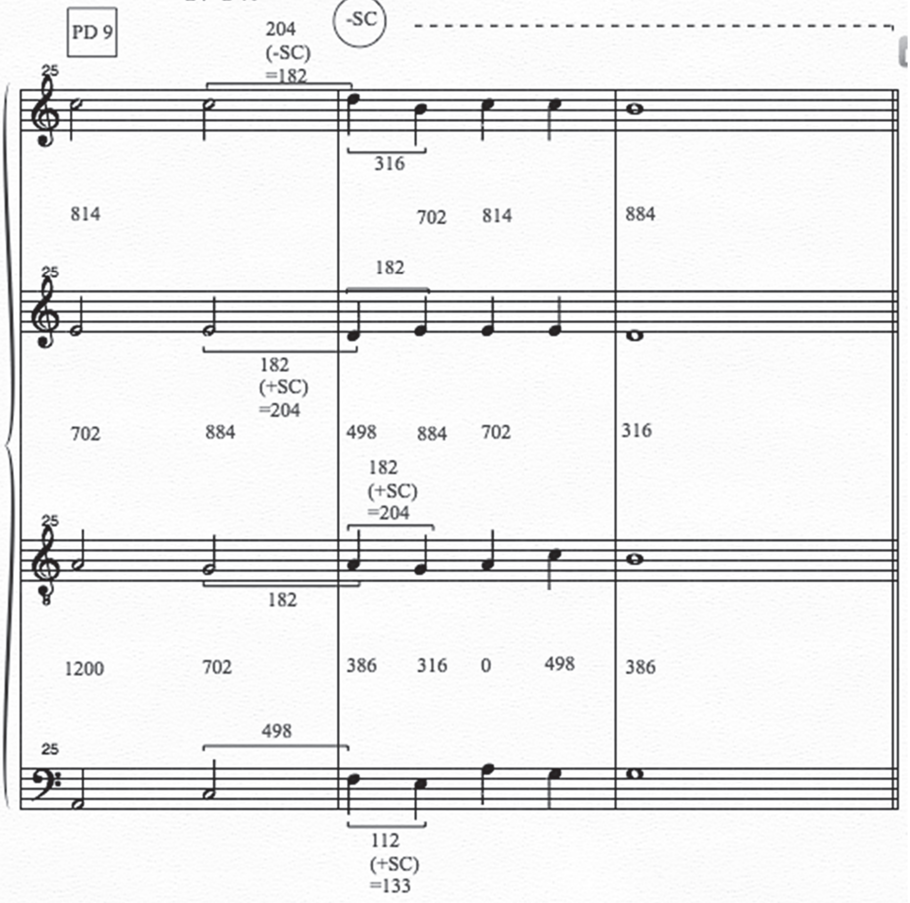

PD 6
I / 9.
-SC
316
(-SC)
= 294
16
204
814
702
814
1200
884
112
(+SC)
=133
16
112
182
(+SC)
=204
16
204
702
0
386
702
316
182
16
884
(+SC)
=906

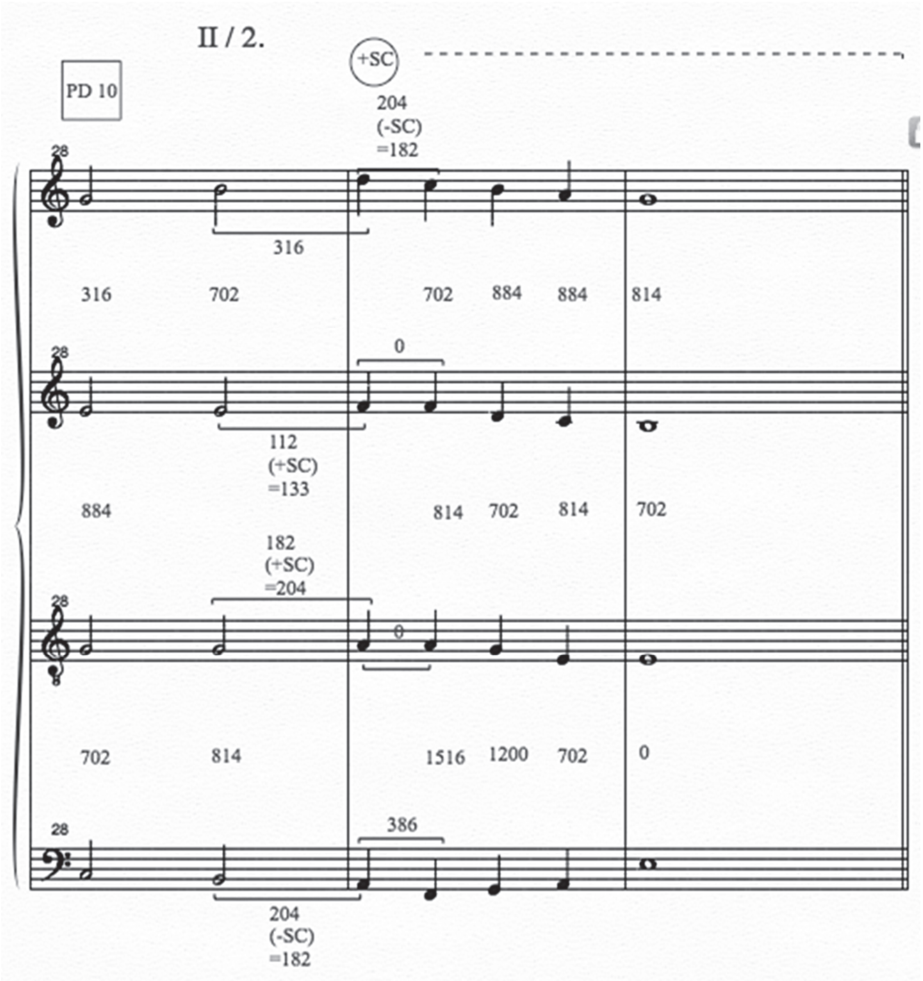

-SC
PD 7
I / 10.
19
182 (+SC) =204
316
814
1200
814
316
498
316
19
182
182 (+SC) =204
884
702
884
498
316
386
204 (-SC) =182
19
182
702
814
702
702
386
1200
498
19
112 (+SC) =133

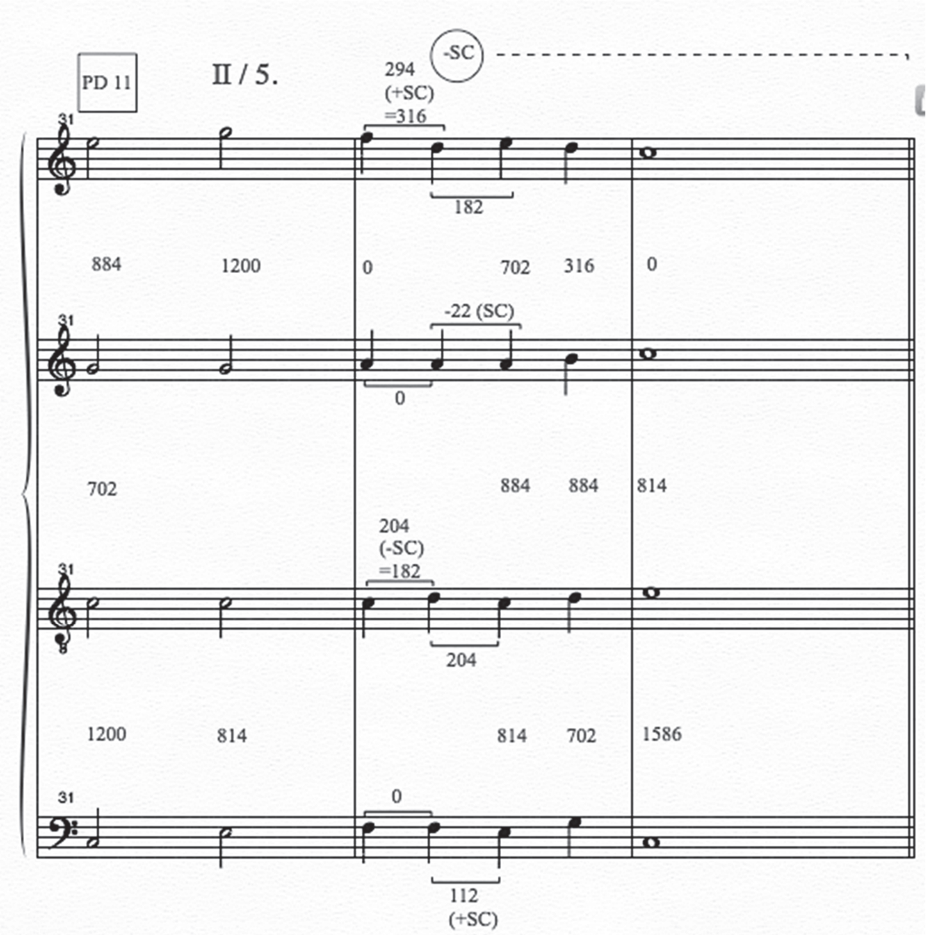
I / 13.


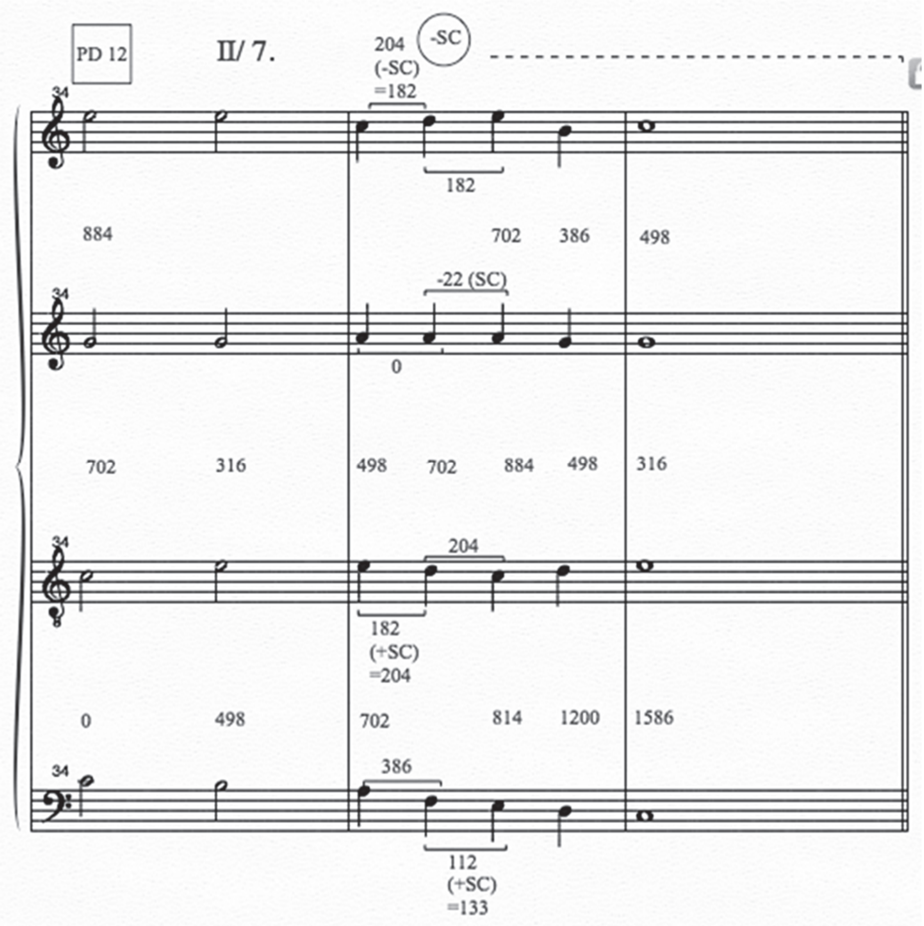
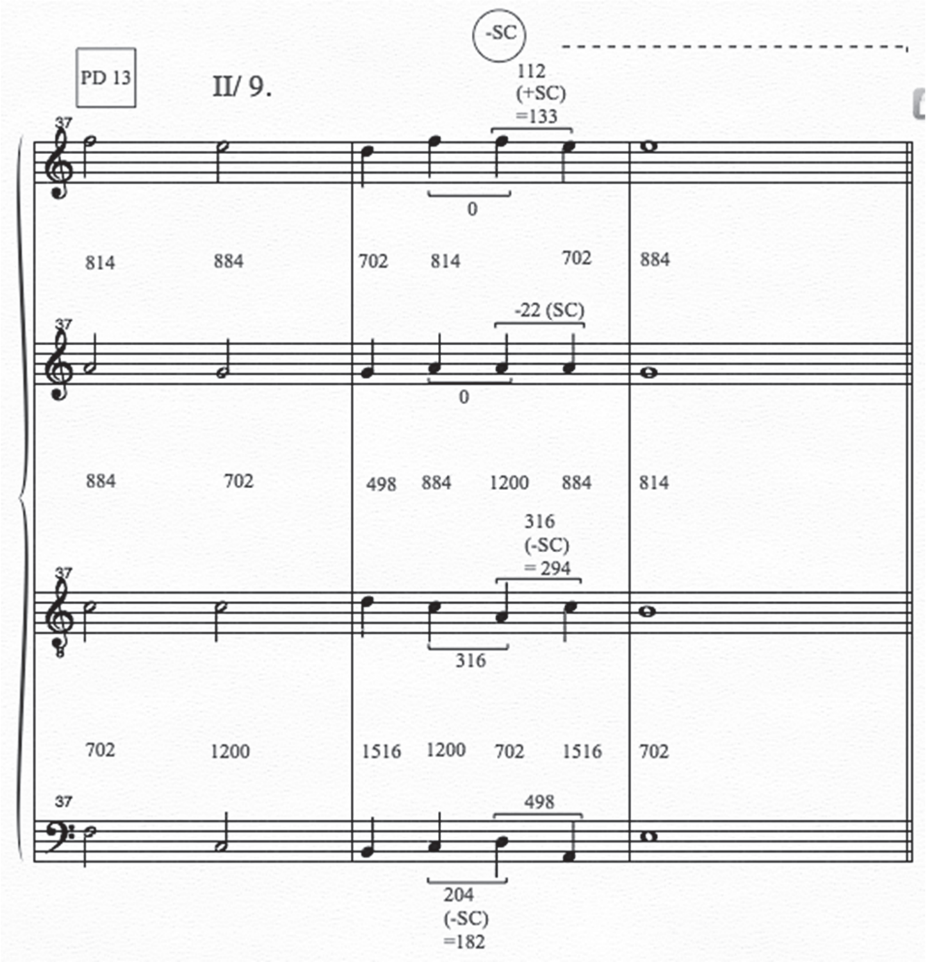
PD 8
-SC
22
316
(-SC)
= 294
182
814
702
884
884
814
702
884
112
204
(-SC)
=182
702
884
814
702
884
814
182
316
(-SC)
= 294
1200
316
702
1200
702
316
702
182
(+SC)
=204
204

I / 14.

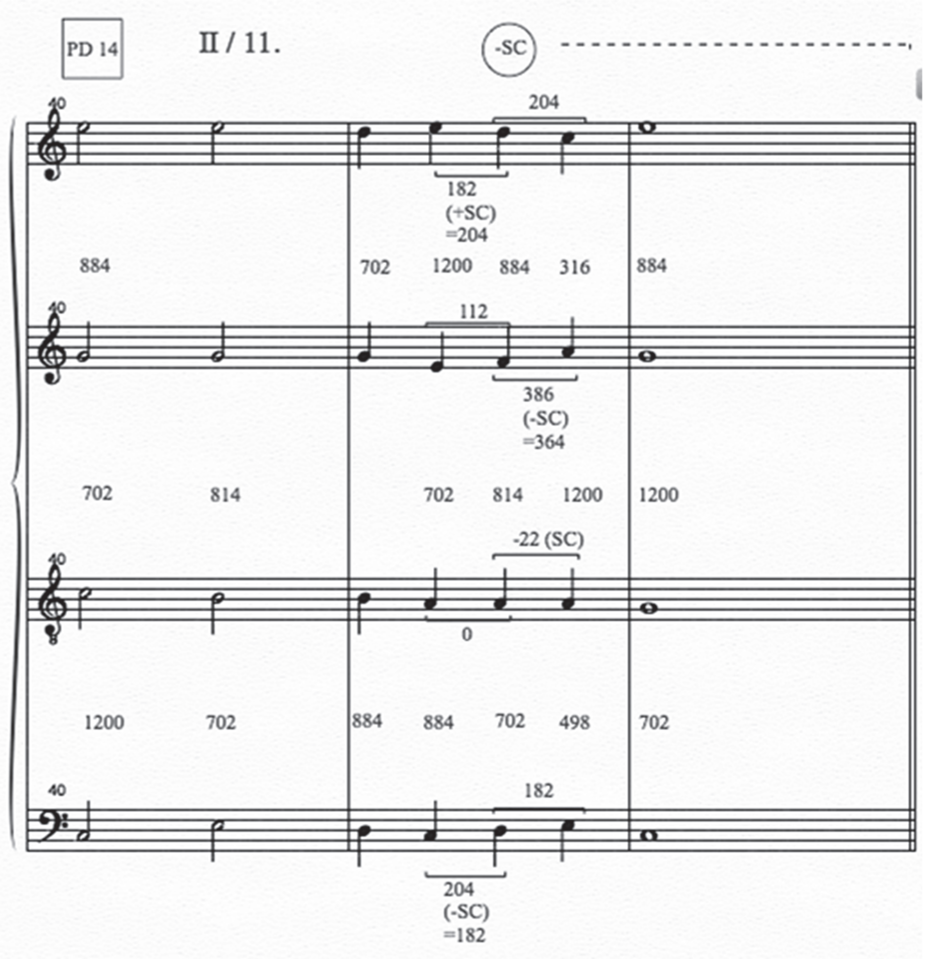

PD 9
-SC
204
(-SC)
=182
25
316
814
702
814
884
25
182
182
(+SC)
=204
702
884
498
884
702
316
182
(+SC)
=204
25
182
1200
702
386
316
0
498
386
25
498
112
(+SC)
=133

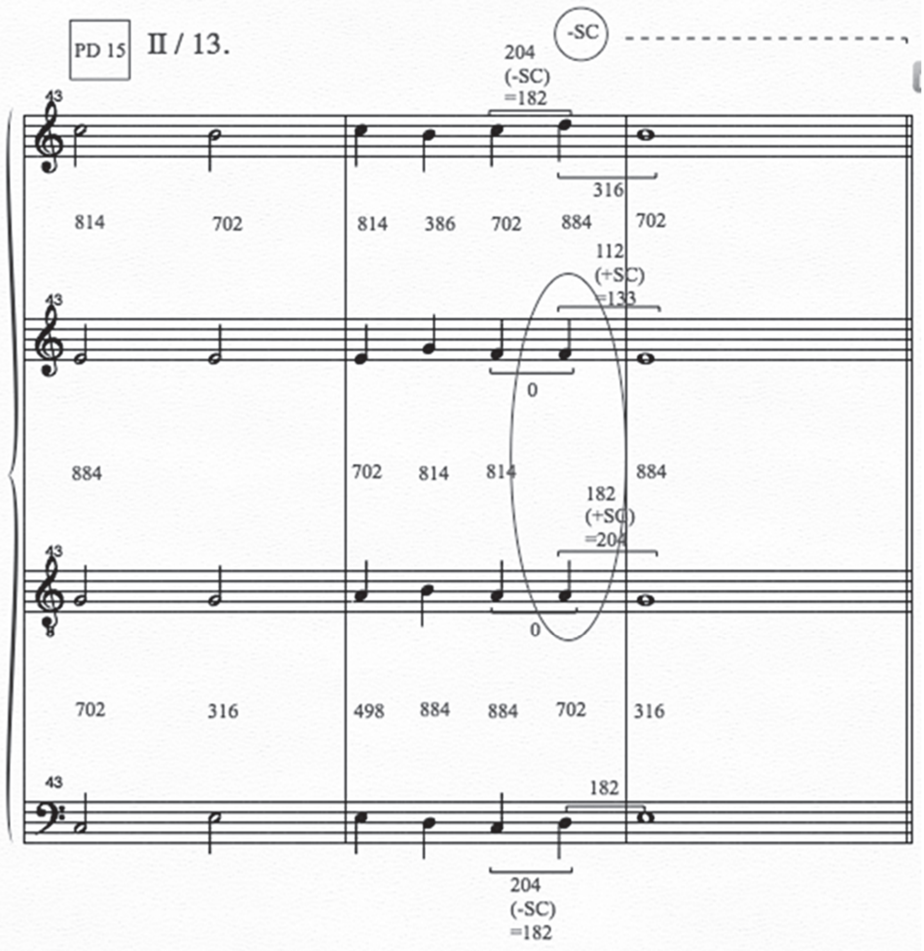

II / 2.
PD 10
+SC
204
(-SC)
=182
28
316
316
702
702
884
884
814
28
0
112
(+SC)
=133
884
814
702
814
702
182
(+SC)
=204
28
0
702
814
1516
1200
702
0
28
386
204
(-SC)
=182


PD 11
II / 5.
-SC
294
(+SC)
=316
31
182
884
1200
0
702
316
0
-22 (SC)
31
0
702
884
884
814
204
(-SC)
=182
31
204
1200
814
814
702
1586
31
0
112
(+SC)


PD 12
II/ 7.
204
(-SC)
=182
-SC
34
182
884
702
386
498
-22 (SC)
34
0
702
316
498
702
884
498
316
204
34
8
182
(+SC)
=204
0
498
702
814
1200
1586
386
34
112
(+SC)
=133


PD 13
II/ 9.
-SC
112
(+SC)
=133
37
0
814
884
702
814
702
884
-22 (SC)
37
0
884
702
498
884
1200
884
814
316
(-SC)
= 294
37
316
702
1200
1516
1200
702
1516
702
498
37
204
(-SC)
=182


PD 14
II / 11.
-SC
40
204
182
(+SC)
=204
884
702
1200
884
316
884
112
386
(-SC)
=364
702
814
702
814
1200
1200
-22 (SC)
0
1200
702
884
884
702
498
702
182
204
(-SC)
=182


PD 15
II / 13.
-SC
204
(-SC)
=182
316
814
702
814
386
702
884
702
112
(+SC)
=133
0
884
702
814
814
884
182
(+SC)
=204
0
702
316
498
884
884
702
316
182
204
(-SC)
=182

Appendix 9.

Table 42. The normality tests of mistuning misattributions to a minor triad and major triad in three categories in Experiment 1.

Data set	Kolmogorov-Smirnov[1]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Minor_CAT1_29	,166	156	,000	,946	156	,000
Minor_CAT2_29	,161	156	,000	,956	156	,000
Minor_CAT3_29	,367	156	,000	,701	156	,000
Major_CAT1_29	,260	156	,000	,761	156	,000
Major_CAT2_29	,254	156	,000	,882	156	,000
Major_CAT3_29	,146	156	,000	,933	156	,000

[1] Lilliefors significance correction

Appendix 10.

Table 43. The normality tests of recognition of mistuning three categories by instruments in Experiment 1.

Data set	Instrument group	Kolmogorov-Smirnov[1]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
SC_All	string instrument	,121	49	,069	,959	49	,087
	brass instrument	,125	16	,200 [2]	,978	16	,948
	woodwind instrument	,125	38	,143	,964	38	,265
	piano, kantele, guitar, harp, percussion	,094	50	,200 [2]	,976	50	,402
SC_All_CAT1	string instrument	,154	49	,005	,937	49	,011
	brass instrument	,172	16	,200 [2]	,954	16	,560
	woodwind instrument	,106	38	,200 [2]	,971	38	,425
	piano, kantele, guitar, harp, percussion	,120	50	,070	,972	50	,273
SC_All_CAT2	string instrument	,183	49	,000	,944	49	,022
	brass instrument	,207	16	,066	,942	16	,375
	woodwind instrument	,187	38	,002	,930	38	,021
	piano, kantele, guitar, harp, percussion	,123	50	,056	,943	50	,017
SC_All_CAT3	string instrument	,150	49	,008	,933	49	,008
	brass instrument	,243	16	,012	,864	16	,022
	woodwind instrument	,129	38	,114	,962	38	,218
	piano, kantele, guitar, harp, percussion	,121	50	,066	,952	50	,043
Minor_All_29	string instrument	,109	49	,200 [2]	,968	49	,206
	brass instrument	,167	16	,200 [2]	,947	16	,447
	woodwind instrument	,114	38	,200 [2]	,951	38	,094
	piano, kantele, guitar, harp, percussion	,112	50	,155	,976	50	,410
Major_All_29	string instrument	,195	49	,000	,909	49	,001

	brass instrument	,187	16	,136	,850	16	,014
	woodwind instrument	,204	38	,000	,922	38	,012
	piano, kantele, guitar, harp, percussion	,124	50	,051	,963	50	,115
Minor_CAT1_29	string instrument	,130	49	,038	,945	49	,024
	brass instrument	,286	16	,001	,817	16	,005
	woodwind instrument	,217	38	,000	,925	38	,014
	piano, kantele, guitar, harp, percussion	,155	50	,004	,944	50	,019
Minor_CAT2_29	string instrument	,157	49	,004	,931	49	,007
	brass instrument	,167	16	,200[2]	,955	16	,565
	woodwind instrument	,241	38	,000	,879	38	,001
	piano, kantele, guitar, harp, percussion	,157	50	,003	,943	50	,018
Minor_CAT3_29	string instrument	,389	49	,000	,680	49	,000
	brass instrument	,236	16	,018	,809	16	,004
	woodwind instrument	,393	38	,000	,621	38	,000
	piano, kantele, guitar, harp, percussion	,367	50	,000	,696	50	,000
Major_CAT1_29	string instrument	,306	49	,000	,729	49	,000
	brass instrument	,216	16	,044	,839	16	,009
	woodwind instrument	,273	38	,000	,798	38	,000
	piano, kantele, guitar, harp, percussion	,291	50	,000	,696	50	,000
Major_CAT2_29	string instrument	,228	49	,000	,888	49	,000
	brass instrument	,326	16	,000	,781	16	,002
	woodwind instrument	,255	38	,000	,876	38	,001
	piano, kantele, guitar, harp, percussion	,249	50	,000	,869	50	,000
Major_CAT3_29	string instrument	,157	49	,004	,938	49	,012
	brass instrument	,213	16	,050	,934	16	,278

	woodwind instrument	,164	38	,011	,942	38	,050
	piano, kantele, guitar, harp, percussion	,162	50	,002	,910	50	,001

[1] Lilliefors significance correction, [2] This is a lower bound of the true significance

Appendix 11.

Table 44. The normality tests of recognition of mistuning three categories, by choir voices, in Experiment 1.

Data set	Choir voice	Kolmogorov-Smirnov[1]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
SC_All	top voice	,097	56	,200[2]	,977	56	,369
	assisting voice	,152	57	,002	,943	57	,010
	bass voice	,100	39	,200[2]	,973	39	,464
SC_All_CAT1	top voice	,100	56	,200[2]	,973	56	,230
	assisting voice	,094	57	,200[2]	,961	57	,065
	bass voice	,128	39	,110	,917	39	,007
SC_All_CAT2	top voice	,132	56	,017	,962	56	,074
	assisting voice	,169	57	,000	,951	57	,021
	bass voice	,145	39	,037	,963	39	,231
SC_All_CAT3	top voice	,134	56	,014	,940	56	,008
	assisting voice	,139	57	,008	,957	57	,042
	bass voice	,164	39	,010	,927	39	,015
Minor_All_29	top voice	,152	56	,002	,965	56	,104
	assisting voice	,132	57	,015	,965	57	,096
	bass voice	,111	39	,200[2]	,975	39	,531
Major_All_29	top voice	,115	56	,061	,941	56	,008
	assisting voice	,186	57	,000	,906	57	,000
	bass voice	,092	39	,200[2]	,978	39	,634
Minor_CAT1_29	top voice	,216	56	,000	,911	56	,001
	assisting voice	,154	57	,002	,937	57	,005
	bass voice	,129	39	,101	,949	39	,077
Minor_CAT2_29	top voice	,169	56	,000	,940	56	,008
	assisting voice	,179	57	,000	,948	57	,017
	bass voice	,127	39	,115	,965	39	,267
Minor_CAT3_29	top voice	,405	56	,000	,657	56	,000
	assisting voice	,380	57	,000	,690	57	,000
	bass voice	,337	39	,000	,706	39	,000

Major_CAT1_29	top voice	,265	56	,000	,803	56	,000
	assisting voice	,264	57	,000	,722	57	,000
	bass voice	,260	39	,000	,777	39	,000
Major_CAT2_29	top voice	,245	56	,000	,898	56	,000
	assisting voice	,266	57	,000	,842	57	,000
	bass voice	,238	39	,000	,894	39	,001
Major_CAT3_29	top voice	,170	56	,000	,933	56	,004
	assisting voice	,162	57	,001	,929	57	,002
	bass voice	,165	39	,009	,910	39	,004

[1] Lilliefors significance correction, [2] This is a lower bound of the true significance

Appendix 12.

Table 45. The normality tests of recognition of mistuning three categories, by gender, in Experiment 1.

Data set	Gender	Kolmogorov-Smirnov[1]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
SC_All	male	,094	51	,200 [2]	,978	51	,472
	female	,127	103	,000	,971	103	,024
SC_All_CAT1	male	,124	51	,049	,960	51	,080
	female	,106	103	,006	,966	103	,009
SC_All_CAT2	male	,126	51	,042	,975	51	,340
	female	,151	103	,000	,974	103	,037
SC_All_CAT3	male	,172	51	,001	,921	51	,002
	female	,120	103	,001	,962	103	,005
Minor_All_29	male	,166	51	,001	,952	51	,040
	female	,140	103	,000	,972	103	,028
Major_All_29	male	,137	51	,019	,916	51	,002
	female	,137	103	,000	,936	103	,000
Minor_CAT1_29	male	,161	51	,002	,951	51	,035
	female	,165	103	,000	,936	103	,000
Minor_CAT2_29	male	,192	51	,000	,951	51	,034
	female	,142	103	,000	,955	103	,002
Minor_CAT3_29	male	,305	51	,000	,740	51	,000
	female	,397	103	,000	,668	103	,000
Major_CAT1_29	male	,278	51	,000	,778	51	,000
	female	,248	103	,000	,739	103	,000
Major_CAT2_29	male	,252	51	,000	,884	51	,000
	female	,252	103	,000	,876	103	,000
Major_CAT3_29	male	,149	51	,006	,936	51	,008
	female	,154	103	,000	,930	103	,000

[1] Lilliefors significance correction, [2] This is a lower bound of the true significance

Appendix 13.

Table 46. Pearson correlations between recognitions in Category 1.

Samples	Correlation ρ	p	N
SC2 - SC5	.199	.011	162
SC2 - SC7	.141		164
SC2 - SC15	.035		163
SC2 - SC16	.131		163
SC2 - SC19	.013		163
SC2 - SC21	.246	.002	163
SC2 - SC22	.144		163
SC2 - SC24	.171	.029	163
SC2 - SC25	.215	.006	163
SC2 - SC26	.123		164
SC2 - SC29	.100		164
SC2 - SC34	.146		164
SC2 - SC35	.068		164
SC2 - SC36	.060		163
SC2 - SC37	.029		162

Appendix 14.

Table 47. Pearson correlations between recognitions in Category 2.

Samples	Correlation ρ	*p*	*N*
SC4 – SC6	.034		165
SC4 – SC8	-.128		165
SC4 – SC9	.257	.001	164
SC4 – SC10	.099		165
SC4 – SC13	-.066		163
SC4 – SC17	.254	.001	165
SC4 – SC18	.099		165
SC4 - SC20	.144		164
SC4 - SC23	.154		165
SC4 - SC27	.141		165
SC4 – SC30	.091		165
SC4 - SC32	-.102		165
SC4 - SC33	.248	.001	165
SC4 - SC39	-.113		165
SC4 – SC40	.121		165

Appendix 15.

Table 48. Pearson correlations between recognitions in Category 3.

Samples	Correlation ρ	*p*	*N*
SC1 – SC3	.155	.047	165
SC1 – SC11	.066		166
SC1 – SC12	-.091		166
SC1 – SC14	.218	.005	166
SC1 – SC28	.114		166
SC1 – SC31	.042		166
SC1 – SC38	.134		166

Appendix 16.

Table 49. Results of the factor analysis of the experiment items representing factors as variables in Experiment 1.

Total Variance Explained

	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
Factor	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5,751	14,377	14,377	1,502	3,754	3,754	1,980	4,950	4,950
2	2,251	5,626	20,003	1,673	4,183	7,937	1,788	4,471	9,421
3	2,049	5,122	25,125	2,882	7,204	15,141	1,656	4,140	13,562
4	1,728	4,320	29,445	1,683	4,208	19,349	1,351	3,378	16,939
5	1,665	4,162	33,607	2,328	5,820	25,169	1,248	3,120	20,059
6	1,560	3,900	37,507	1,253	3,132	28,301	1,236	3,090	23,148
7	1,455	3,638	41,144	1,209	3,023	31,325	1,200	3,000	26,148
8	1,415	3,538	44,683	1,076	2,690	34,014	1,171	2,926	29,074
9	1,334	3,334	48,017	,891	2,227	36,241	1,129	2,824	31,898
10	1,320	3,299	51,316	,915	2,287	38,528	1,080	2,700	34,598
11	1,232	3,079	54,395	,843	2,109	40,637	1,060	2,649	37,247
12	1,155	2,888	57,283	,690	1,725	42,362	1,052	2,631	39,878
13	1,134	2,834	60,118	,696	1,739	44,101	,990	2,475	42,353
14	1,031	2,578	62,696	,648	1,620	45,721	,979	2,446	44,799
15	1,021	2,552	65,248	,537	1,342	47,063	,906	2,264	47,063
16	,946	2,366	67,614						
17	,910	2,275	69,888						
18	,900	2,249	72,138						
19	,864	2,161	74,299						
20	,826	2,065	76,363						
21	,776	1,941	78,304						
22	,735	1,838	80,143						
23	,727	1,817	81,960						
24	,661	1,652	83,612						
25	,633	1,582	85,194						
26	,616	1,541	86,735						
27	,580	1,451	88,185						
28	,533	1,334	89,519						
29	,504	1,261	90,779						
30	,473	1,183	91,963						
31	,428	1,071	93,033						
32	,409	1,021	94,055						
33	,406	1,014	95,069						
34	,388	,969	96,038						
35	,338	,846	96,884						
36	,336	,840	97,724						
37	,258	,645	98,369						
38	,235	,587	98,955						
39	,227	,566	99,522						
40	,191	,478	100,000						

Extraction Method: Maximum Likelihood.

Appendix 16 continues.

Rotated Factor Matrix [a]

	Factor														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SC27	,685	,076	,060	-,026	,025	,040	,004	-,051	,129	,137	,027	-,022	-,062	,029	-,036
SC3	,493	,156	,193	,443	,028	,154	,151	,259	-,067	-,035	,126	,134	,085	,022	,041
SC30	,475	,303	,077	,056	,044	,107	,030	,132	,303	,145	-,017	,090	,087	-,078	-,116
SC34	,451	-,012	,207	,260	,074	,002	-,010	,067	,042	-,075	,044	,047	,056	,014	,080
SC12	,329	,160	-,009	,049	,000	,033	-,040	-,293	-,007	-,045	,107	-,117	-,094	,048	-,041
SC40	,321	,154	,102	,035	,025	,093	,041	,028	-,008	,072	,076	,123	,110	,028	,262
SC38	,292	,089	,263	,141	,029	,088	,192	,155	-,051	,045	,061	,093	-,195	-,018	,009
SC15	,127	,721	,122	,179	-,098	-,062	,056	,150	-,034	,101	,133	,106	-,038	-,092	,043
SC26	,162	,540	,011	,091	,043	,044	,094	,154	,110	-,176	-,024	,395	,087	,096	,243
SC36	,117	,441	,284	-,130	,042	,111	,055	-,031	-,014	-,018	-,078	,054	,103	,270	,059
SC35	,079	,420	-,084	,141	,095	,035	,036	-,035	,076	,016	-,031	-,098	,009	,131	-,132
SC28	,243	,289	,590	,073	,064	,193	,118	,302	,237	,098	-,004	,050	,053	-,056	,174
SC31	,096	,001	,537	,141	,002	-,099	-,094	-,074	,017	,069	,055	-,059	,100	,206	,004
SC14	,335	,158	,481	,094	,075	,090	,097	,125	,005	,043	,017	,138	-,075	-,027	-,176
SC10	-,006	-,050	,377	,052	,097	,098	,042	-,090	-,072	-,003	-,001	,233	,024	-,003	-,042
SC32	-,084	-,023	-,320	,041	-,058	-,020	-,090	-,265	-,092	,082	-,127	,007	,140	,162	-,031
SC20	,150	,244	,089	,733	,017	,078	-,007	,066	,119	,152	,070	-,019	-,025	-,048	,082
SC37	,033	-,067	-,169	-,400	-,175	-,078	,185	,038	,092	,043	-,014	,182	,244	,318	,145
SC5	,187	,285	,035	,288	,058	,166	,062	-,021	,249	,140	-,125	,253	,168	,063	,104
SC16	,119	,006	,135	,228	-,036	,131	-,081	-,046	,046	-,142	,105	,134	,053	,015	,044
SC4	,116	,013	,117	,061	,960	-,076	,050	,124	-,013	,066	,101	,029	-,034	,001	,080
SC22	-,047	,116	,169	,114	-,003	,631	-,066	,119	-,060	,016	,012	-,033	,032	,133	-,122
SC6	,189	-,023	-,066	,000	,013	,472	-,009	-,087	,035	,171	,081	,076	,117	-,024	-,019
SC7	,125	-,001	,028	,085	-,138	,328	,175	,046	,197	-,060	-,040	-,069	,002	,107	,070
SC39	-,042	-,136	-,070	,054	-,046	,006	-,974	-,068	,054	-,054	,001	,034	-,044	-,083	-,020
SC23	,035	,100	-,018	,043	,043	,047	,039	,688	-,052	,095	,018	,007	,026	,090	-,019
SC17	,096	,094	,114	,109	,186	-,105	-,018	,322	-,158	,147	,039	,090	-,179	,047	,233
SC8	-,002	,024	-,119	-,011	-,127	,017	-,032	-,029	,520	-,096	-,061	,008	,005	,057	-,029
SC19	,075	-,005	,064	,041	,008	-,098	-,067	-,001	,401	,115	,009	-,083	-,074	,141	-,094
SC33	,120	,096	,155	,036	,210	,135	,042	-,041	,397	,024	,016	-,004	,090	-,089	,018
SC2	,055	-,039	,097	,160	,123	,279	,102	-,092	,336	,105	,239	,167	,035	,103	-,026
SC21	,211	,049	,091	,110	,065	,223	,062	,233	,055	,852	,105	,069	,073	,074	-,143
SC11	,141	,025	,076	,095	,089	,067	-,008	,038	-,052	,062	,911	,009	,051	-,100	,021
SC1	,050	,076	,107	-,004	,016	-,022	-,042	,064	-,044	,053	,025	,696	-,012	-,004	-,131
SC29	-,035	,147	,123	-,022	,030	,177	,026	,001	-,004	,030	,043	,056	,690	,033	-,027
SC9	-,049	,180	,149	-,042	,258	,141	-,054	,003	-,010	-,071	-,009	,207	-,335	,096	,076
SC24	,016	,170	,085	-,049	,015	,189	,077	,089	,179	,041	-,089	,004	-,021	,714	,056
SC25	-,024	,066	,142	-,052	,082	,135	,073	,038	,138	,087	,005	,124	-,142	,191	-,472
SC18	-,017	,011	,013	,032	,084	,010	,045	,056	-,010	-,066	,014	-,045	-,120	,138	,427
SC13	,215	-,101	-,093	,115	-,095	,165	-,060	,133	,014	-,193	,100	,037	,251	,009	-,284

Extraction Method: Maximum Likelihood.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 39 iterations.

Appendix 17.

Table 50. The normality tests for pitch drift preferences, local tempering preferences, equal temperament preferences, and meantone tuning preferences by choir background in Experiment 2.

Preferences by tuning alternative	Kolmogorov-Smirnov[5]	Shapiro-Wilk
PD[1] preferences		
with choir background	[K-S(50) = .16, p < .01]	[S-W(50) = .94, p < .05]
no choir background	[K-S(42) = .21, p < .001)	[S-W(42) = 91, p < .01]
LT[2] preferences		
with choir background	[K-S(50) = .14, p < .05	[S-W(50) = .92, p < .01]
no choir background		
ET[3] preferences		
with choir background	[K-S(50) = .11, p > .05]	[S-W(50) = .98, p > .05]
no choir background	([K-S(42) = .13, p > .05]	[S-W(42) = .95, p > .05]
MT[4] preferences		
with choir background	[K-S(50) = .13, p < .05]	[S-W(50) = .97, p > .05]
no choir background	[K-S(42) = .13, p > .05]	[S-W(42) = .96, p > .05]

[1] PD = pitch drift, [2] LT = local tempering, [3] ET = equal temperament, [4] MT = meantone tuning

[5] Lilliefors significance correction

Appendix 18.

Table 51. Normality tests or pitch drift preferences, local tempering preferences, equal temperament preferences, and meantone tuning preferences explored by gender in Experiment 2.

Preferences by tuning alternative	Kolmogorov-Smirnov[5]	Shapiro-Wilk
PD[1] preferences		
male	[K-S(23) = .25, p < .001]	[S-W(23) = .85, p < .01]
female	[K-S(69) = .20 p < .001]	[S-W(69) = .92, p < .001].
LT[2] preferences		
male	[K-S(23) = .18, . p < .05]	S-W(69) = .94, p < .05]
female	K-S(69) = .13, p < .01]	[S-W(69) = .94, p < .01].
ET[3] preferences		
male	[K-S(23) = .19, p > .05]	[S-W(23) = .97, p > .05]
female	[K-S(69) = .12, p < .05)	[S-W(69) = .98, p > .05]
MT[4] preferences		
male	[K-S(23) = -.18, p > .05]	[S-W(23) = -.90, p < .05].
female	(K-S(69) = .13, p < .01	[S-W(69) = .95, p < .01]

[1] PD = pitch drift, [2] LT = local tempering, [3] ET = equal temperament, [4] MT = meantone tuning

[5] Lilliefors significance correction

Appendix 19.

Table 52. The results of normality tests for distributions of all experiment blocks of the four tuning alternatives in Experiment 2.

Tuning alternative	Experiment block 1	Experiment block 2	Experiment block 3	Experiment block 4	Experiment block 5
	1–6	7–12	13–18	19–24	25–30
PD[1]	K-S(92) = .26	K-S(92) = .32	K-S(92) = .28	K-S(92) = .40	K-S(92) = .26
	$p < .00$	$p < .001$	$p < .001$	$p < .001$	$p < .001$
	S-W(92) = .80,	S-W(92) = .75,	S-W(92) = .77,	S-W(92) = .80,	S-W(92) = .83,
	$p < .001$	$p < .001$	$p < .001$	$p < .001$	$p < .001$
LT[2]	K-S(92) = .26	K-S(92) = .22	K-S(92) = .27	K-S(92) = .33	K-S(92) = .27
	$p < .001$	$p < .001$	$p < .001$	$p < .001$	$p < .001$
	S-W(92) = .87	S-W(92) = .85	S-W(92) = .86	S-W(92) = .81	S-W(92) = .86
	$p < .001$	$p < .001$	$p < .001$	$p < .001$	$p < .001$
ET[3]	K-S(92) = .25	K-S(92) = .24	K-S(92) = .27	K-S(92) = .24	K-S(92) = .27
	$p < .001$	$p < .001$	$p < .001$	$p < .001$	$p < .001$
	S-W(92) = .87	S-W(92) = .82	S-W(92) = .83	S-W(92) = .83	S-W(92) = .86
	$p < .001$	$p < .001$	$p < .001$	$p < .001$	$p < .001$
MT[4]	K-S(92) = .26	K-S(92) = .34	K-S(92) = .26	K-S(92) = .30	K-S(92) = .22
	$p < .001$	$p < .001$	$p < .001$	$p < .001$	$p < .001$
	S-W(92) = .83	S-W(92) = .79	S-W(92) = .83	S-W(92) = .75	S-W(92) = .83
	$p < .001$	$p < .001$	$p < .001$	$p < .001$	$p < .001$

[1] PD = pitch drift, [2] LT = local tempering, [3] ET = equal temperament, [4] MT = meantone tuning

Appendix 20.

Table 53. Results of the factor analysis of the experiment items representing factors as variables in Experiment 2.

Total Variance Explained

	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3,524	11,746	11,746	3,524	11,746	11,746	2,412	8,040	8,040
2	1,973	6,576	18,322	1,973	6,576	18,322	2,106	7,019	15,059
3	1,886	6,288	24,610	1,886	6,288	24,610	1,689	5,631	20,690
4	1,802	6,008	30,618	1,802	6,008	30,618	1,620	5,400	26,089
5	1,741	5,803	36,421	1,741	5,803	36,421	1,603	5,343	31,433
6	1,711	5,702	42,123	1,711	5,702	42,123	1,586	5,285	36,718
7	1,456	4,853	46,976	1,456	4,853	46,976	1,585	5,285	42,003
8	1,311	4,370	51,346	1,311	4,370	51,346	1,540	5,135	47,138
9	1,279	4,263	55,609	1,279	4,263	55,609	1,509	5,032	52,169
10	1,208	4,026	59,635	1,208	4,026	59,635	1,451	4,837	57,006
11	1,126	3,755	63,390	1,126	3,755	63,390	1,370	4,567	61,573
12	1,101	3,672	67,061	1,101	3,672	67,061	1,344	4,479	66,052
13	1,026	3,419	70,480	1,026	3,419	70,480	1,329	4,429	70,480
14	,954	3,179	73,659						
15	,888	2,961	76,620						
16	,853	2,843	79,462						
17	,751	2,504	81,967						
18	,673	2,243	84,209						
19	,613	2,045	86,254						
20	,590	1,966	88,220						
21	,535	1,783	90,003						
22	,488	1,626	91,629						
23	,444	1,479	93,109						
24	,429	1,431	94,539						
25	,374	1,247	95,787						
26	,342	1,142	96,928						
27	,291	,969	97,897						
28	,263	,876	98,773						
29	,203	,677	99,450						
30	,165	,550	100,000						

Extraction Method: Principal Component Analysis.

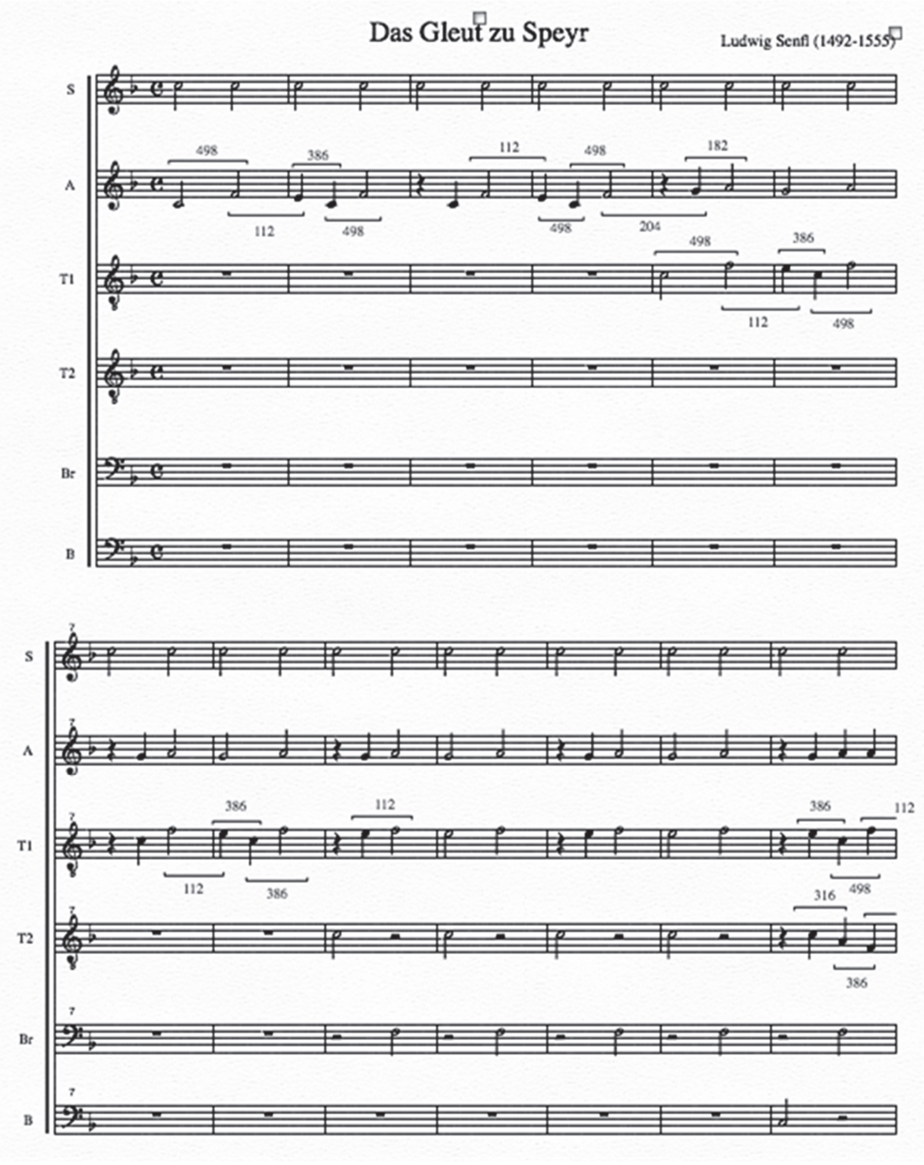
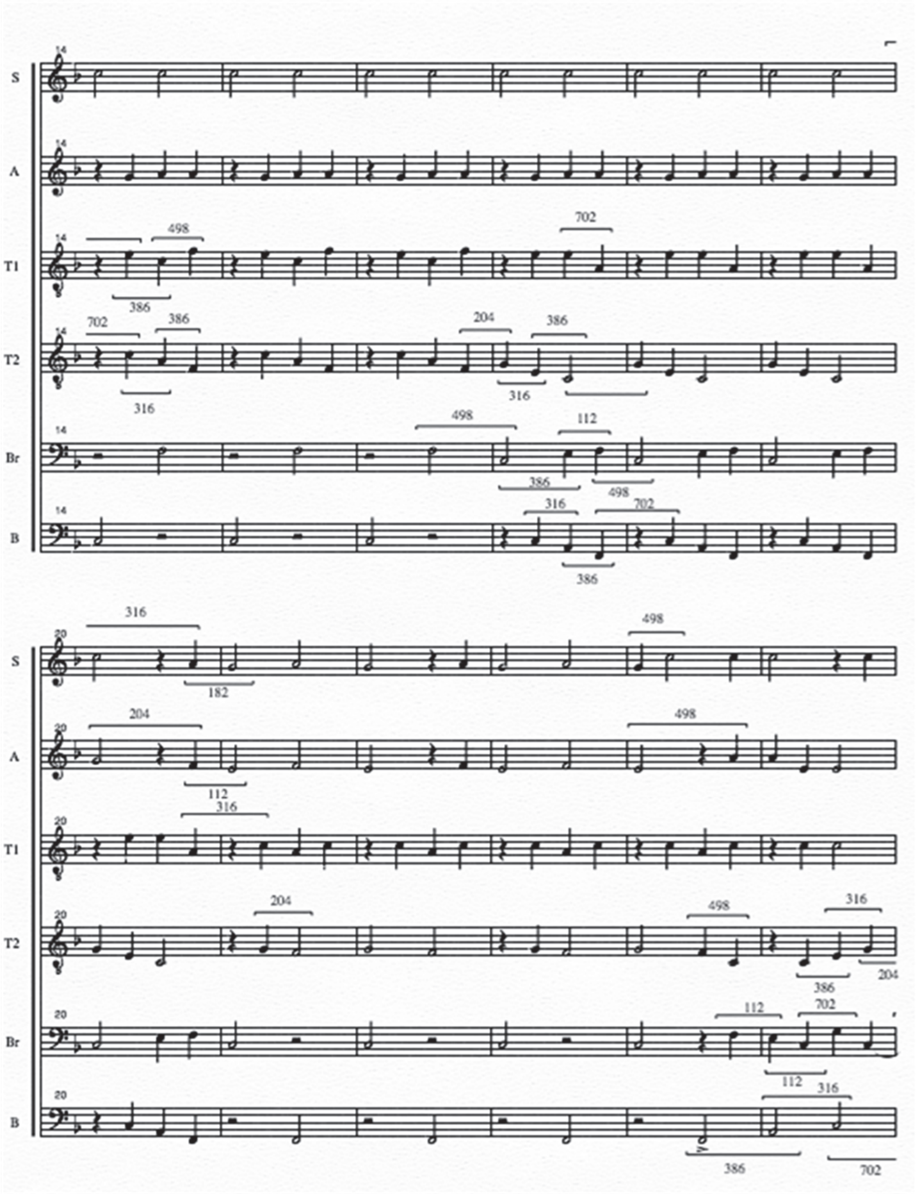
Appendix 20 continues.

Rotated Component Matrix [a]

	Component												
	1	2	3	4	5	6	7	8	9	10	11	12	13
PD_ET3	,795	,216	-,072	-,055	-,050	,136	,026	,123	-,158	,040	-,014	,146	-,076
LT_ET4	,729	-,010	,140	,000	,098	,058	-,046	-,008	,232	,126	-,083	-,101	-,013
MT_PD4	,575	,196	-,077	-,008	-,237	-,074	,013	,060	,141	-,094	,446	,128	-,137
PD_MT3	,480	,058	,330	,053	-,226	-,007	,176	-,335	,183	-,184	,105	,058	,262
PD_MT1	,058	,772	,152	,056	,029	,290	-,036	-,068	,045	,091	-,005	-,035	,194
ET_PD2	,031	,737	-,244	-,146	-,012	-,160	,081	,020	,200	,040	,032	,122	,069
ET_PD4	,333	,677	,028	,320	,120	-,131	,034	,136	-,046	-,133	,106	,074	-,045
MT_PD2	,439	,475	,032	-,043	-,335	,168	,042	,238	-,320	,051	-,026	-,141	-,145
LT_PD5	-,068	-,038	,707	-,124	-,023	-,025	,147	,107	,098	,073	-,106	-,235	-,274
LT_MT3	,200	-,059	,675	-,042	-,009	-,057	-,121	-,066	-,144	-,098	-,131	,110	,188
PD_ET5	-,068	,111	,483	,108	,154	,343	-,211	-,190	,181	-,015	,264	,230	-,032
ET_MT3	-,004	,047	-,089	,799	,028	,096	-,080	-,009	-,032	-,033	,099	-,013	,039
MT_ET4	-,138	-,004	,070	,516	,140	-,107	-,090	-,111	-,190	,018	-,339	,306	-,097
MT_LT2	-,059	,058	-,022	,043	,867	,070	,053	,014	,026	,008	,010	-,036	,085
LT_ET2	,113	-,002	-,021	,019	,065	,854	,112	,013	,109	,059	,072	-,034	-,054
PD_LT4	,165	,076	-,005	,248	-,318	,386	,254	,151	-,309	-,141	,182	,269	,097
ET_LT1	,008	,048	,068	-,023	,010	,086	,799	,123	-,059	,224	,023	,008	,076
ET_MT5	-,027	,019	,252	,292	-,132	-,063	-,631	,278	-,095	,258	-,131	-,072	,135
PD_ET1	,016	,040	-,082	-,024	,115	-,180	,203	,776	,074	-,157	,108	,058	-,039
LT_MT5	,115	,041	,065	-,001	-,190	,252	-,181	,689	-,006	,036	-,082	,017	,207
LT_PD3	,160	,099	,014	-,068	,035	,095	-,004	,032	,825	-,053	-,033	,001	-,046
MT_ET2	,239	-,045	,138	,104	,382	-,153	-,002	-,149	-,403	-,280	,066	-,141	-,310
ET_LT3	-,083	,166	,293	,338	-,252	-,042	,333	,031	,351	,269	,100	,026	-,283
LT_MT1	,310	-,149	,060	,101	,131	-,194	,121	,019	-,019	,695	,108	,129	,041
ET_LT5	-,112	,178	-,100	-,111	-,110	,223	,028	-,148	,003	,682	-,072	-,098	-,097
LT_PD1	,001	,045	-,118	,086	,001	,132	,116	,015	-,051	-,008	,755	,041	-,009
PD_MT5	,070	,085	-,149	,324	-,217	,263	,333	,058	,124	-,189	-,482	,096	-,107
MT_LT4	-,125	-,019	,061	-,123	,139	,058	-,054	-,086	-,072	-,069	-,055	-,795	,145
PD_LT2	-,161	,188	,154	-,350	,269	,234	,021	-,071	-,116	-,183	-,069	,493	,051
ET_MT1	-,097	,146	-,018	-,003	,086	-,058	,014	,098	-,033	-,039	,007	-,141	,857

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 20 iterations.

Appendix 21. Music without syntonic commas, Ludwig Senfl: Das Gleut zu Speyr


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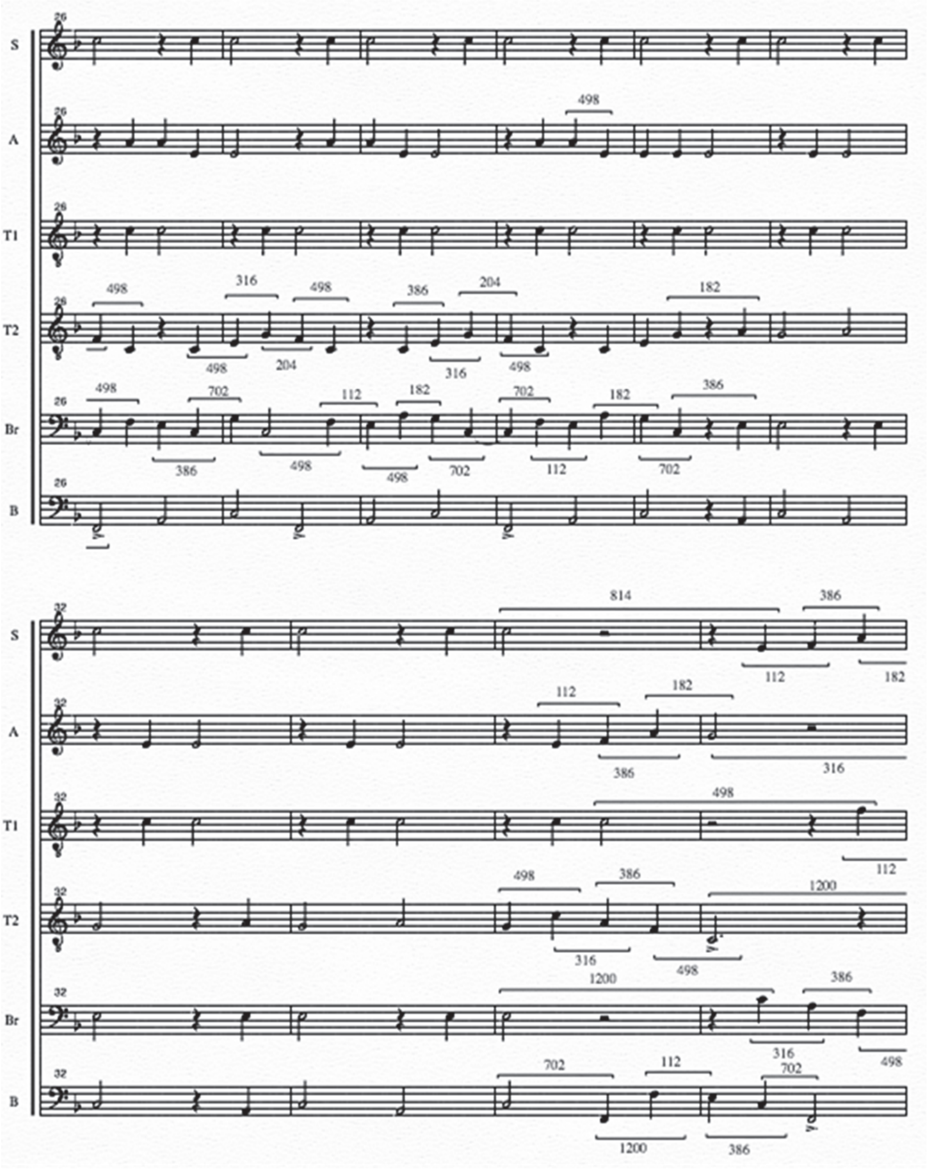

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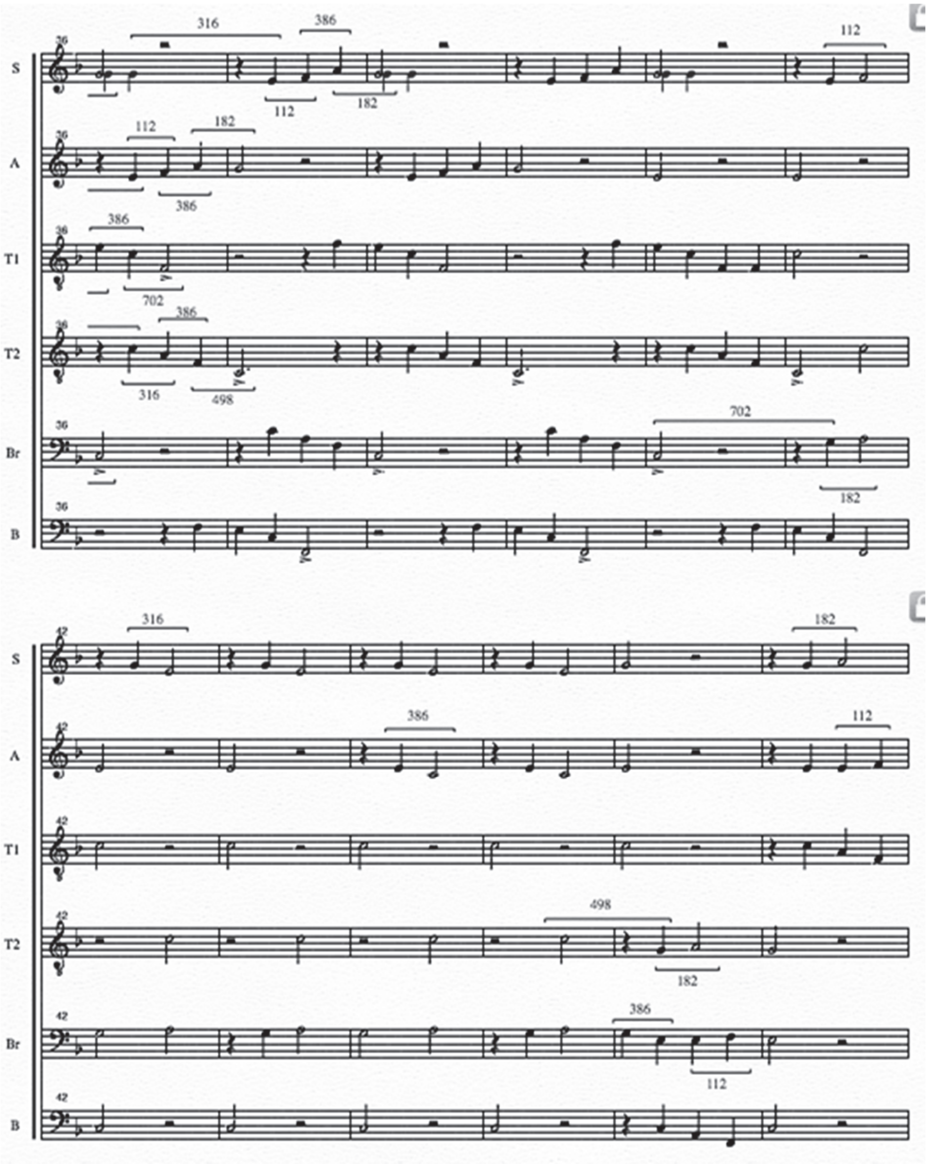

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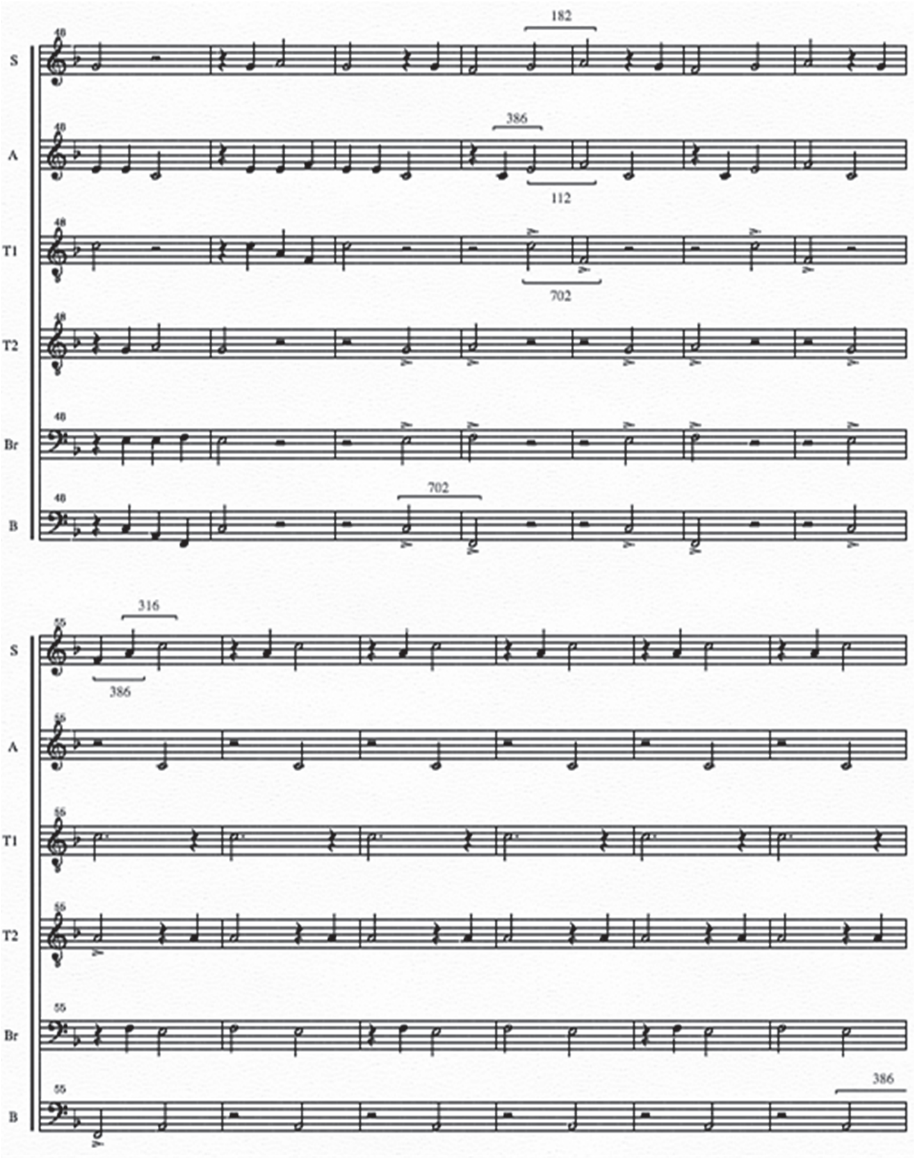

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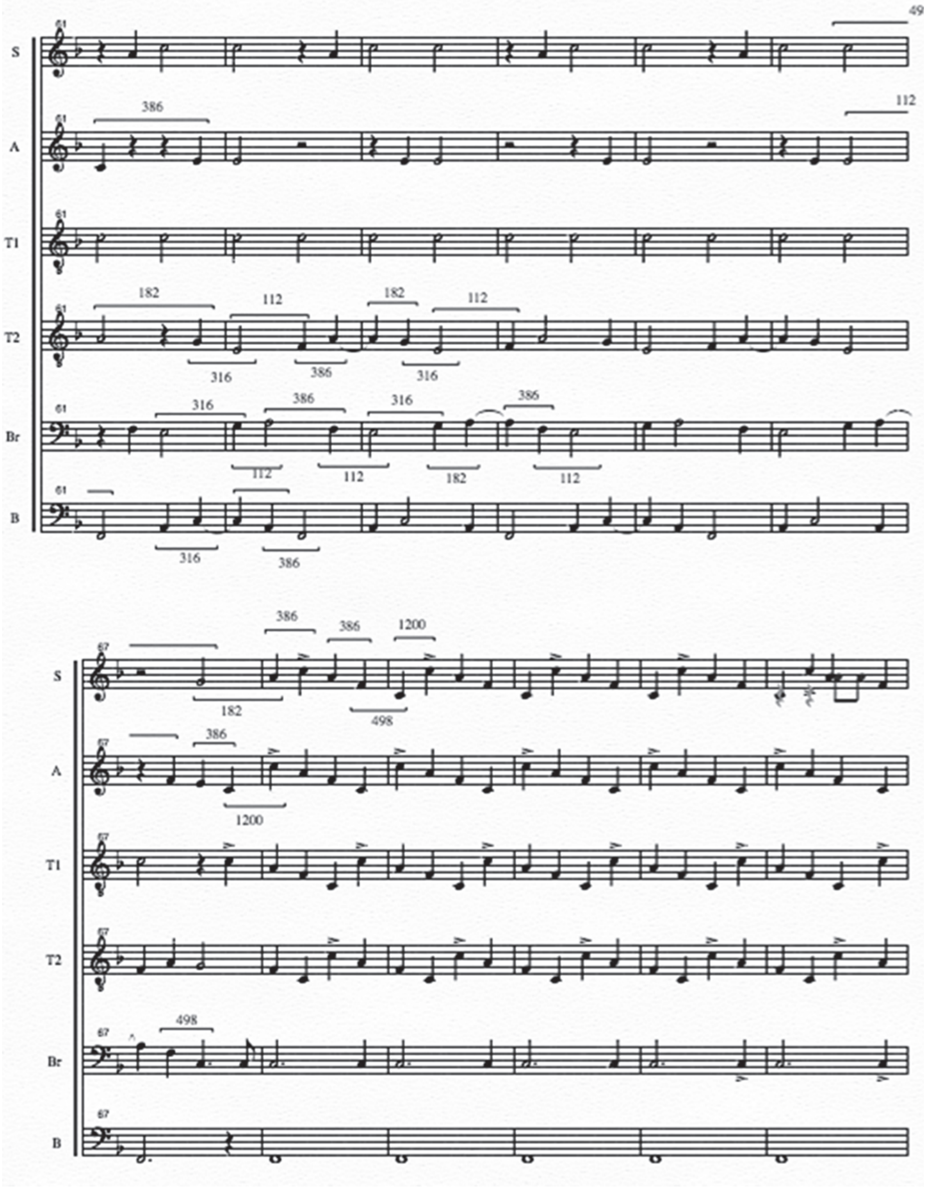
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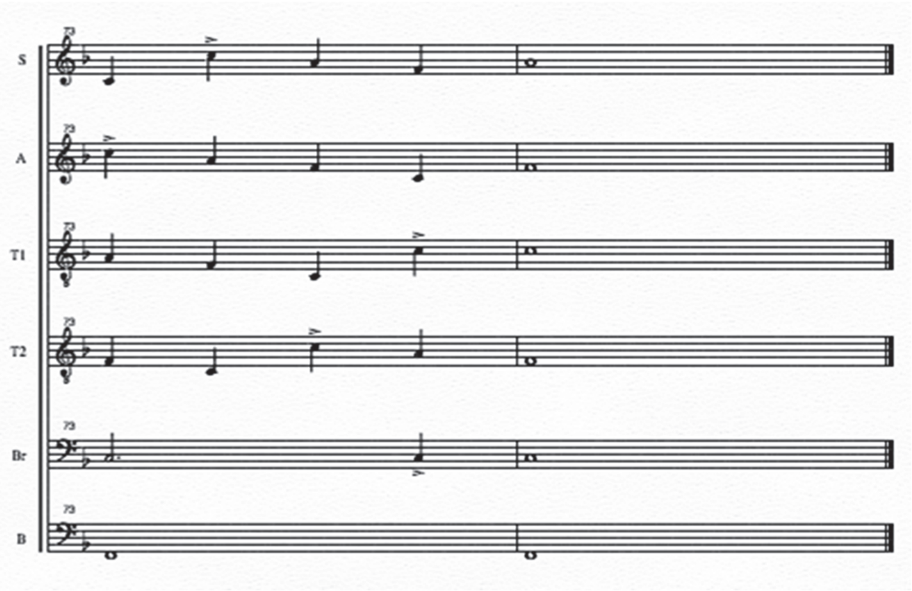

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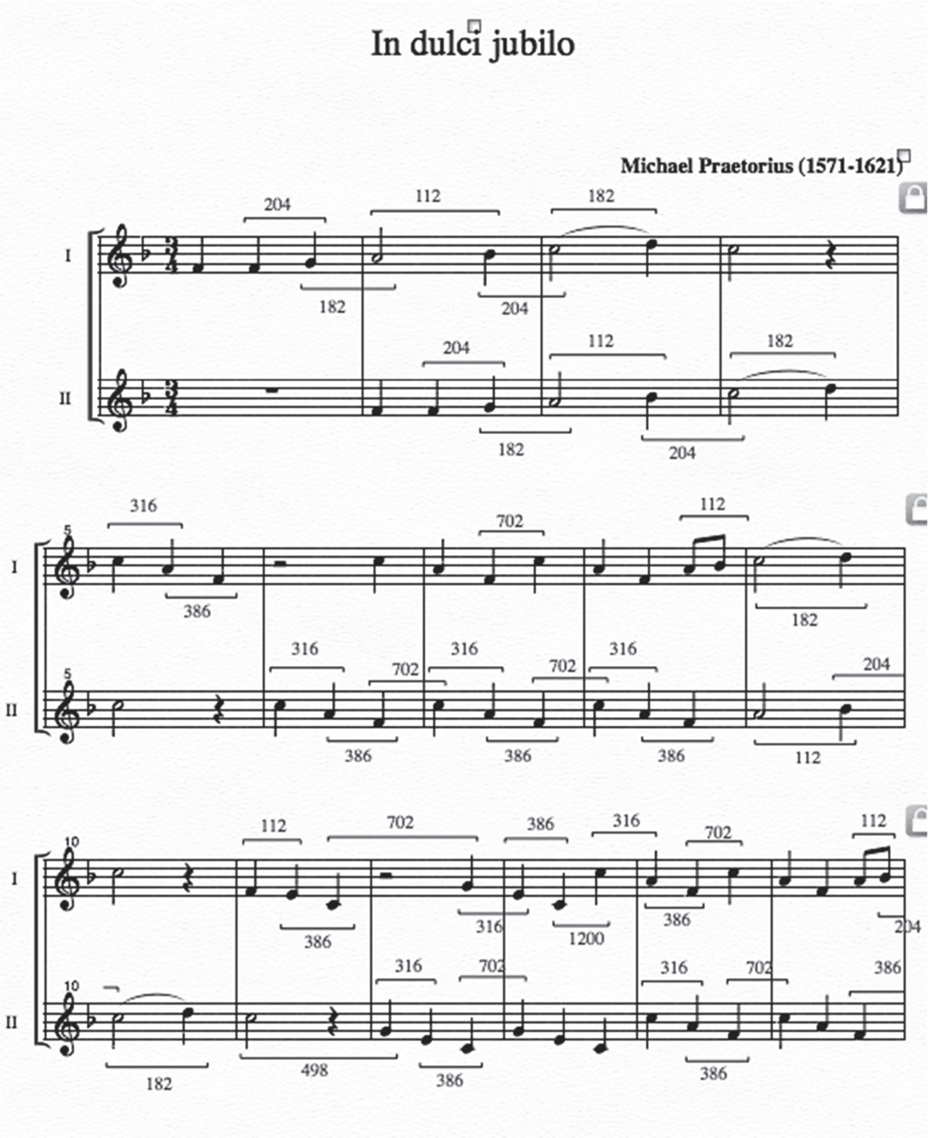
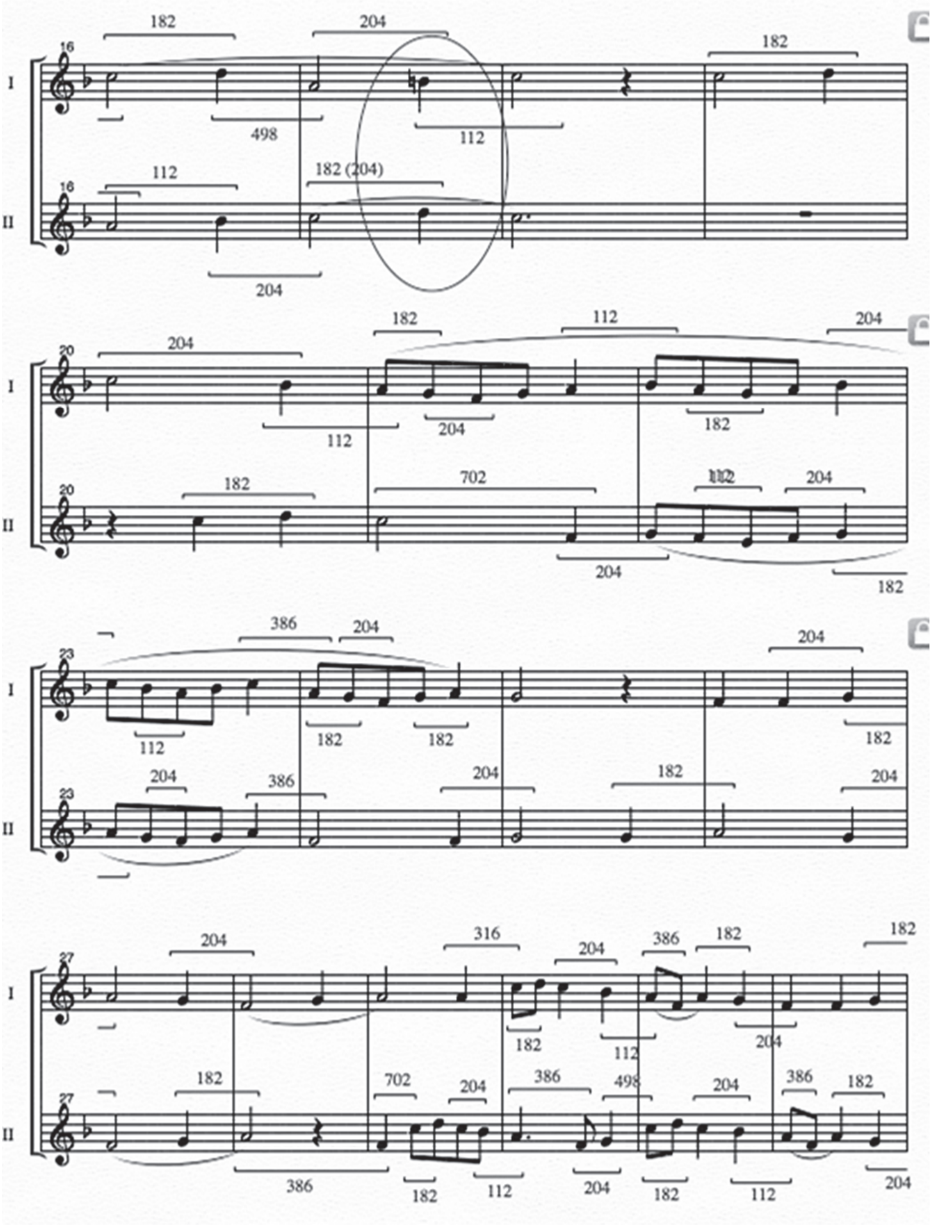
Appendix 22. Music without syntonic commas, Michael Praetorius: In dulci jubilo


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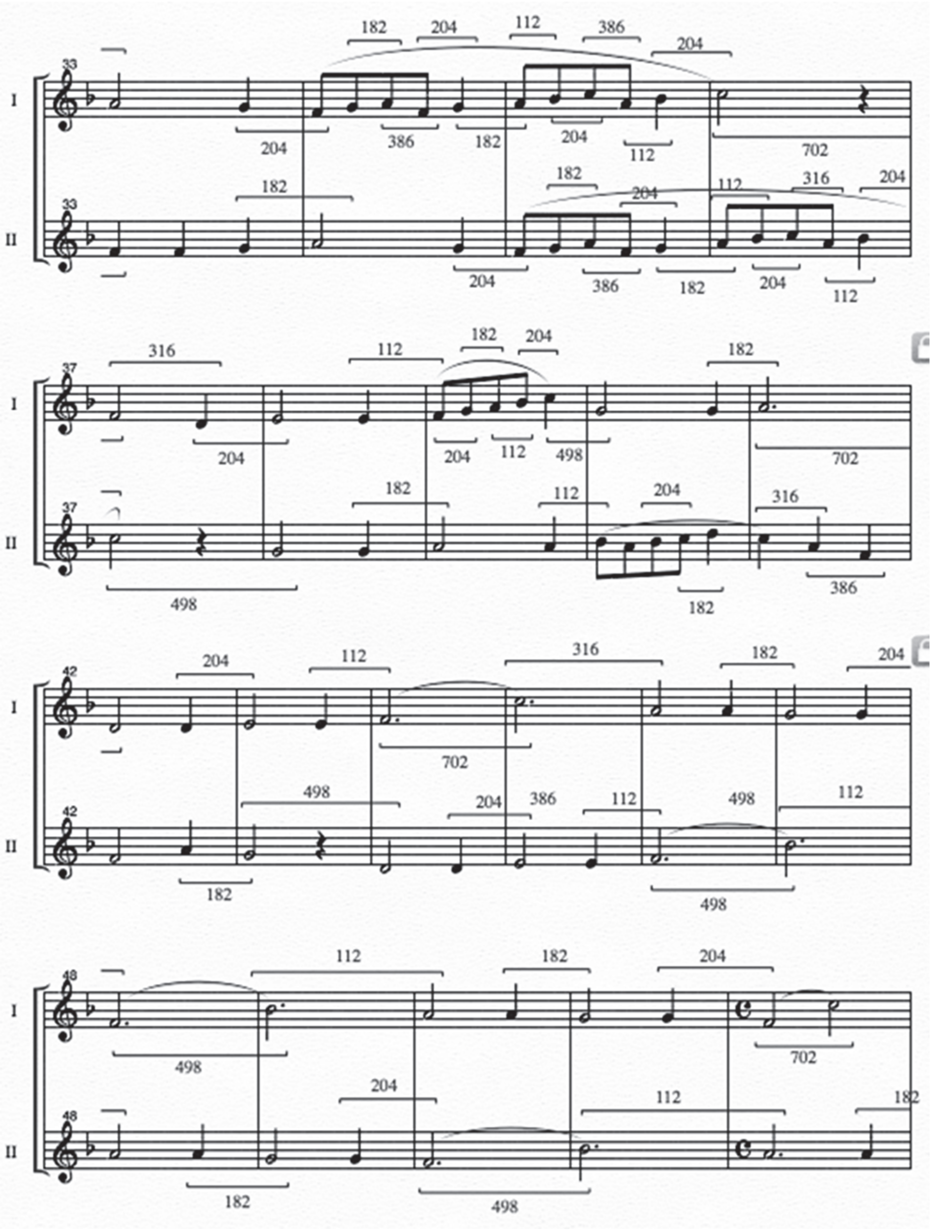

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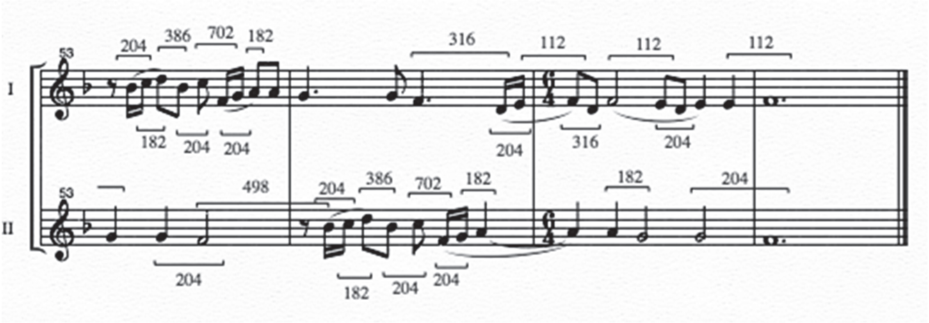

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