Vertical dissonance as an alternative harmonic-related perceptual feature

DM2906 Individual Course in Media Technology

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Abstract
The purpose of this study is to explore how well dissonance fits as an alternative for a harmonic-related perceptual feature that is easily rated by human listeners. Dissonance is a well-known concept, often described as a sensation of roughness, tension and unpleasantness. For example, dissonant intervals comprised of complex tones have partials that don’t align and therefore give rise to beating. These intervals are also characterised by having complex ratios and have been avoided in classical music for a long time. Furthermore, dissonance may be regarded as the vertical dimension of harmony, with melody and chord progression being the horizontal. In an experiment, 32 listeners rated the dissonance of 92 isolated two- and three-note chords (dyads and triads). Preliminary results show that dissonance was easy for the listeners to rate, which possibly makes it suitable to use as a perceptual feature in future experiments. Furthermore, it was shown that triads, with some limitations, may be regarded as a combination of dyads.

Introduction
In the field of music information retrieval, a lot of ambition has been put into finding suitable and general terms to describe music from the perceptual perspective. In Friberg et al. (2014) nine perceptual features are proposed on the basis of an ecological approach. That is, the idea that we listen to properties of the sound source rather than just properties of the timbre. This is motivated by the idea that this is closer to how humans perceive sound and thus provides a good basis for the rating of features in music. The perceptual features proposed were dynamics, modality (minor-majorness), rhythmic complexity, speed, rhythmic clarity, brightness (timbre), pitch, articulation and harmonic complexity. These were estimated using audio features and compared to human ratings. Harmonic complexity was used as a perceptual feature, which encompasses both the vertical and horizontal dimensions of harmony. Vertical harmony is the perception of simultaneous notes whereas horizontal harmony is the harmonic sequence of notes (chord progression and melodies). In the study by Friberg et al. (2014), harmonic complexity was presumed to be difficult to rate, because it refers to a complex music theoretical analysis involving chord changes and key
deviations. This was confirmed in their study in which harmonic complexity obtained the lowest mean pair-wise inter-subject correlation of 0.21. It was suggested that future studies investigate alternative perceptual features for describing harmonic-related perceptual features.

The main idea of the present study is to further investigate the perceptual grounds on which we classify music and to find an alternative approach for a harmonic-related perceptual feature. In other words, can dissonance be used as a replacement for the vertical dimension of harmony in the perceptual feature set? The focus is on short sequences ignoring key-relations and harmonic progression. In a sense, this may be regarded as the vertical aspect of harmony in contrast to the horizontal aspect, which deals with cadences and melody. Specifically, the present study will investigate how well dissonance may be used as a perceptual feature by checking inter-rater agreement levels when rating two- and three-note chords (dyads and triads). The dyad and triad case are also compared to see how combinations of intervals with different levels of dissonance contribute to the total level of dissonance.

**Previous work**

**Dissonance**

Consonance is often described as the absence of annoying factors (Terhardt, 1984) or as harmony or agreement among components and literally means sounding together, indicating that there should be no clash between sound components. Bones & Plack (2015) describe consonance as perception of resolution and stability. In experiments performed by Plomp & Levelt (1965) the definition that was given to the test subjects was that consonance is the same as beautiful or euphonious. This definition was justified by stating that those terms were highly correlated for naïve subjects. This definition of consonance is problematic since we know that dissonant pieces of music still are regarded as euphonious and beautiful. Sethares (1992, 1993) describes dissonant intervals as rough, unpleasant, tense and unresolved, a definition that presumably allows a wider account of dissonance. On a more mathematical level, intervals that are characterised by simple frequency ratios are regarded as consonant. This was known already to Pythagoras, who made experiments by making divisions of the string of a monochord. The basic idea is that the smaller the numbers in which the frequency ratios may be expressed, the more consonant that interval is. Thus the octave, with a frequency ratio of 1:2, is the most consonant interval (Plomp & Levelt, 1965).

Terhardt (1984) regards musical consonance as a two-component concept consisting of sensory consonance and harmony. Sensory consonance is not music specific, unlike the harmony component. He states that the nature of consonance must be considered unknown and that it is the principle that creates the specific frequency relations that are the basis of tonal music and that musical consonance is representing essential features in it. But at the same time, Terhardt states that it can be reduced to psychoacoustical factors such as pitch and roughness. The notion of musical consonance as having two components is further developed by Fastl and Zwicker
(2007), who also regard it as being based on sensory consonance and harmony. Harmony, in turn, is based on tonal affinity, compatibility and root relationship. Thompson (2009) regards sensory and musical forms of consonance as overlapping but that the former are a result of psychoacoustical factors and the latter as dependent on musical experience.

**Roughness**

Roughness is a concept closely related to dissonance. Helmholtz (1895) proposed that it is the beating of adjacent partials, roughness, in complex tones that causes the sensation of dissonance. Most following studies on the subject are based on the theories of Helmholtz. For pure sinusoidal tones, the sensation of roughness, reach a maximum when the amplitude fluctuations perceived as beats are at 35 Hz, according to Helmholtz. Later studies, such as Zwicker & Fastl (2007), put the roughness maximum at 70 Hz. For small frequency differences the beats between two simple tones can be heard individually as amplitude fluctuations. This evolves into the sensation of roughness as the distance increases. As frequency increases beyond the maximum, roughness decreases and consonance increases, irrespectively of frequency (Plomp & Levelt, 1965). This is in contrast to Helmholtz proposal that the frequency difference for maximum roughness is independent of frequency. Instead, Plomp & Levelt proposed that the frequency difference should be proportional to the critical bandwidth.

According to Zwicker and Fastl (2007), the sensation of roughness is produced by modulation in the range of 15-300 Hz. At frequencies below 15 Hz, something called fluctuation strength is instead perceived, which is related to vibrato (for frequency modulation) and tremolo (for amplitude modulation) and reaches its maximum around 4 Hz. Roughness reaches its maximum at 70 Hz. From around 150 Hz two distinct tones start to appear and at 300 Hz the sensation of roughness disappears. The sensation of roughness may also be enticed by narrow-band noise, which implies that the signal does not need to be periodical in all cases. Roughness is described as unpleasant by Roederer (1995) and as a buzzing quality (Vassilakis, 2010). Bones & Plack (2015) showed that pleasantness ratings are similar to roughness and dissonance ratings of other studies, with the minor second being the least pleasant and the perfect fifth being the most pleasant.

In the western music tradition, auditory or sensory roughness is one of the perceptual correlates of dissonance. According to Vassilakis & Kendall (2010), sensory dissonance is the attribute of dissonance that best correlates to roughness. Vassilakis (2005) argues that a clear presence or absence of roughness is the main factor in dissonance ratings. When dealing with isolated harmonic intervals, dissonance ratings are dominated by roughness factors for non-ambiguous levels of roughness. Vassilakis (2001) states that roughness provides the primary cue for dissonance, based on an experiment in which two groups rated roughness and dissonance, respectively.

It may be regarded as problematic that many studies have dealt mainly with pure sinusoidal tones or complex tones synthesized with a set number of harmonic partials
rather than real musical instruments. Previous studies have shown that by keeping a low note at constant pitch and varying an upper note from unison and up that perceived roughness and dissonance quickly increases to its maximum at the minor second interval and then decreasing (Plomp & Levelt, 1965, Sethares 1993, Terhardt 1984). The perceived roughness and dissonance has a minimum at unison and though it decreases continuously after the minor second it never quite reaches the same minimum. For complex tones with harmonic partials the maximum roughness and dissonance is still at the minor second, but the dissonance curve now shows clear dips at the musical intervals. The most consonant intervals are shown to be unison, octave, fifth and fourth. Intervals considered less consonant are still shown to be more consonant than the tones in between them (Plomp & Levelt, 1965, Sethares 1993, Terhardt 1984).

**Sensory consonance and pleasantness in tonal music**

Sensory consonance and dissonance is related to roughness and sharpness and is regarded as “more basic” and related to auditory sensation, according to Terhardt (1984). Every pair of adjacent partials contributes to the perceived roughness. For complex tones, dissonance minima are reached when partials are aligned. The evaluated consonance of isolated chords is controlled by the sensation of roughness, regardless of pure or complex tone dyads. When the total complexity of the spectrum increases something else happens. For a complex spectrum created by more than two tones, having vibrato applied or by several instruments creating chorus effects total roughness may be reduced. Just some adjacent partials will not create an overall sensation of roughness and thus no consonance peaks will appear either. According to Terhardt (1984), this shows that sensory consonance is not only dependent on musical intervals but also on the overall spectra. Therefore, Terhardt argues that one may not draw the conclusion that harmonic intervals typically are created by sensory consonance. It is more related to an overall sensory pleasantness.

A dissonant interval is most simply described as two tones with a complex frequency ratio. For example the most consonant interval, the octave has a ratio of 2:1, whereas a minor second has a frequency ratio of 16:15. Intervals having complex ratios give rise to the sensation of beating, roughness and dissonance, as the basilar membrane is unable to resolve all frequency components (Thompson, 2009). Bones & Plack (2015) argue that the sensation of consonance arise from that the combined spectra of consonant intervals resemble a single complex tone. For dissonant intervals, several partials will be misaligned, and give rise to multiple dissonances. Furthermore, the difference between dissonant and consonant intervals is related to critical bands. If the frequency differences of the interval are outside of the critical bandwidth it is evaluated as consonant. Maximum dissonance is achieved when the frequency difference of the interval is a quarter of the critical bandwidth, according to Plomp & Levelt (1965). Lastly, dissonance varies with frequency. Below 100 Hz even the octave starts to sound dissonant. Also, less simple intervals are even more dependent on frequency.
Sensory pleasantness is presumably relatively easy to rate for listeners but there is some overlap with timbre/brightness. According to Zwicker and Fastl (2007), sensory pleasantness is a complex sensation influenced by sharpness, roughness, tonality and loudness. Increased sharpness decreases sensory pleasantness and is mainly influenced by the overall spectral envelope. Basically, if the spectral envelope is tilted upwards in high frequencies it has more sharpness. Tonality, in Zwicker and Fastl’s account, is regarded as the feature distinguishing the qualities of noise on one hand and tone on the other. Loudness also seems to have influence sensory pleasantness but only at high levels (above 20 sones). Roughness is the second most influential feature on sensory pleasantness after sharpness and is the subject of the following section.

**Tension**

Dissonance is also connected to the notion of tension in music. According to Bigand et al. (1996) there are four main variables for measuring musical tension: tonal hierarchies, sensory consonance-dissonance, horizontal motion and musical training. For musical chords presented in isolation sensory dissonance is regarded as “the most apparent factor” contributing to the perceived tension of that chord. Dissonant chords may however still be stable in a tonal sense. Bigand et al (1996) found a weak but significant relation between musical tension and roughness for musicians, but not for musically naïve subjects. This further implies the importance of musical training for consonance-dissonance. Bigand et al (1996) found three perceptual features that influences perceived musical tension. The first is sensory consonance-dissonance, the second deals with pitch commonality in successive chords and the third deals with horizontal motion. In another study by Bigand & Parncutt (1999) it is concluded that local structures have greater influence on the perception of tonal forms than global structures. Musical tension is determined locally by harmonic cadences and by the perceived local harmonic stability. The pitch commonality factor is less active for long chord sequences than short. However, Dibben (1999) found that sensory consonance, according to the Hutchinson and Knopoff (1978) model, is not a good measure of musical tension. Similarly, roughness of isolated chords is however not a good measurement of the stability and tension at that point as stability is of temporal character, according to Vassiliakis (2001).

In a study on how isolated chords conveyed emotions, Lahdelma and Eerola (2015), participants rated emotions of isolated chords. One of the rated emotions was tension. It was shown that perceived tension was high for chords containing dissonant intervals. The augmented triad received the highest tension ratings followed by the diminished triad. The major triad received the lowest tension rating.

**Scales and tuning**

Furthermore, dissonance and roughness are related to scales and tuning. In just intonation, the frequency ratios of the intervals are constructed to be of small integer ratios, which are defined as a source of consonance in several accounts. The intervals of the twelve-tone equal temperament are slightly more complicated. What intervals are consonant and how good an instrument fits in a scale also depends on the tuning of the instrument and how its partials are distributed. Therefore, the timbre of an instrument is crucial for what scales it is suited for. Sethares (1992, 1993) made
experiments with different scales than just the 12-tone equal temperament. It was
found that in order to make instruments fit in other scales, the distribution of partials
also needs to be altered. Sethares proposes a local principle of consonance, which tells
how consonant a timbre is with a specific tuning or scale.

Dissonance is however not solely determined by the sensation of roughness, but of
several parameters. It is very much based on our musical background and training.
Also, it is connected to our expectations. If we hear a major chord more often than a
minor we will regard it as more “natural” and thus less dissonant (Huron 2006). Thus,
in the context of western musical theory and our expectations, we know which
intervals are supposed to be consonant. Until the renaissance, only the octave, fifth
and fourth intervals were considered consonant. But at this point also thirds and sixths
started to be regarded as “mild” consonances. This terminology is also extended to
dissonances, which may be regarded as mild and sharp (Krenek, 1940). This account
of consonant and dissonant intervals does not include the tritone (i.e. the augmented
fourth or diminished fifth), which is avoided in most classical music as it is
considered too dissonant.

Many previous studies have focused on simple sinusoidals or synthesised complex
tones with a set number of partials at harmonic intervals. This has little relevance to
real life situations with real instruments as these tones are seldom encountered in
classical music. The present study is instead focused on string instruments and more
specifically the piano. String instruments usually have a slightly inharmonic
spectrum, which is often preferred in a musical context (Fastl & Zwicker, 2007). It is
the stiffness of the string that causes inharmonicity by stretching the partials to a
higher frequency than the harmonic frequencies of an ideal string. This also leads to
stretched scales. This inharmonicity thus disfigures the ideal of perfectly consonant
intervals for string instruments.

Conclusively, a lot of different terms have been introduced, with dissonance and
roughness being the most central. The connections between psychophysical and
cultural aspects of dissonance show that this is indeed a complex subject. In the
following chapter, an experiment was setup to see how listeners rated sampled piano
dyad and triad chords.

**Experiment design**

The main idea for the experiment was to have listeners rate real life musical notes. As
most previous studies deal with pure sinusoidals or synthesized complex tones with
harmonic spectra (Vassilakis is an exception) it is hard to tell if the dissonance ratings
are musically relevant. Several sampled piano triad and dyad chords were presented to
listeners. The listening test consisted of 92 examples containing two sets of 46 chords
presented a fifth apart to reduce the influence from absolute pitch. The dyads and
triads were constructed based on the notion of mild and sharp dissonances as
suggested by Krenek (1940). Intervals are divided into consonants, dissonances of
lower tension (mild) and dissonances of higher tension (sharp). This gives three categories of dyads:

1. Consonances: Unison, Minor Third, Major Third, Perfect fourth, Perfect fifth, Minor Sixth, Major Sixth, and Octave.

Krenek regards the tritone or diminished fifth/augmented fourth as neutral, but in this study it is regarded as a sharp dissonance a priori. Also, Krenek regards the perfect fourth as sometimes consonant and sometimes dissonant depending on context. In this study, the perfect fourth is regarded as consonant as only the vertical dimension is considered. The choice of using Krenek’s notion of mild and sharp dissonances was taken to provide a comparison basis for the dissonance ratings.

For triads, each triad would accordingly contain three different dyads. Based on this, we classified the triads in six categories:

1. Three consonances.
2. Two consonances and one mild dissonance.
3. One consonance and two mild dissonances.
4. Two consonances and one sharp dissonance.
5. One consonance, one mild and one sharp dissonance.
6. One mild and two sharp dissonances.

The dyads were named after their abbreviated interval e.g. major seventh is called M7, the minor second is called m2 and the perfect fifth P5 (see figure 1). The triads were named from the dyads of which they consist e.g. the major triad is called M3,m3,P5 (see figure 2). The dyads were centred on middle C and as the interval increased so did the distance of both notes from middle C. This was done in order to avoid having a common root note for all dyads. The intervals ranged from unison (0 semitones) to a major tenth (16 semitones). This was repeated one fifth above middle C giving a total of 34 dyad stimuli. The triads were created similarly by varying root note but keeping the chord centred around middle C and repeated one fifth above middle C. A total of 58 triads were created. All samples were created using the built in sampled piano in Ableton Live and mixed to mono to ensure diotic presentation. The samples were 0.5 seconds long and were normalised by setting the peak of the sound envelope to the same dB value.

The sound clips were presented to listeners in an online test. The participants were given the definition “dissonant intervals are often described as rough, unpleasant, tense and unresolved”, which is based on Sethares (1992, 1993) definition. Initially, participants were asked to calibrate their headphones by adjusting the volume so they barely heard a synthesised sawtooth reference tone. In this way, the listening condition was approximately the same for all listeners. Then they were asked general questions on age, gender identity, their musical training: none, beginner, intermediate
or professional and finally how many hours of active listening they did in a typical week. This was followed by a warm up session with six examples that a priori were considered to be either very dissonant or consonant. The entire set of 92 examples followed. They were presented in a random order, allowing the listener to play the example multiple times before continuing to the next. Each example had a corresponding slider marked “Not dissonant at all” to the left and “Completely dissonant” to the right, see Figure 1. Listeners were not allowed to proceed until the slider had been moved.

![Figure 1: A screenshot of the listening test user interface.](image)

**Listeners**

32 participants were recruited through the author’s personal network. 7 of those were female, the mean age was 29.5 years (SD=5.7) and they practiced an instrument 4 hours a week on average (SD=6). Four participants (one female) were removed from the result due to having answered either too random or too extremely.

**Results**

In order to check inter-rater reliability Cronbach $\alpha$ was calculated for dyads and triads both separate and together (see Table 1).

<table>
<thead>
<tr>
<th></th>
<th>Cronbach $\alpha$</th>
</tr>
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<tbody>
<tr>
<td>Dyads</td>
<td>0.74135</td>
</tr>
<tr>
<td>Triads</td>
<td>0.89637</td>
</tr>
<tr>
<td>Dyads &amp; Triads</td>
<td>0.94968</td>
</tr>
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</table>
As we can see in figure 2, the distribution of dissonance ratings varies between dyads and triads. The participants rate dyads as less dissonant than triads, with a large part of the ratings close “not dissonant at all”. Based on the histogram for the entire set, the triads were regarded as more dissonant in general.

The resulting average ratings are presented in Figure 3 and 4. Based on the assumption that the mean of a series of ratings will form a normal distribution but that the standard deviation of the population is unknown the ratings are assumed to have a t-distribution. This allows the calculation of a confidence interval for dyads and triads respectively (see figures 3 and 4).

The mean rating of each dyad and triad is also presented in tables two and three, together with their corresponding category, as suggested by Krenek. It is evident that the minor second and minor? ninth is rated as most dissonant. The unison was least dissonant followed by the octave and fifth.
Table 2: Mean rated dissonance for dyads and their Krenek categories. The categories are 1: consonances; 2: mild dissonances; 3: sharp dissonances.

<table>
<thead>
<tr>
<th>Dyad</th>
<th>Category</th>
<th>Dissonance</th>
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<tbody>
<tr>
<td>U</td>
<td>1</td>
<td>0.0607</td>
</tr>
<tr>
<td>m2</td>
<td>3</td>
<td>0.7639</td>
</tr>
<tr>
<td>M2</td>
<td>2</td>
<td>0.6600</td>
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<tr>
<td>m3</td>
<td>1</td>
<td>0.3146</td>
</tr>
<tr>
<td>M3</td>
<td>1</td>
<td>0.2479</td>
</tr>
<tr>
<td>P4</td>
<td>1</td>
<td>0.2314</td>
</tr>
<tr>
<td>TT</td>
<td>1</td>
<td>0.4386</td>
</tr>
<tr>
<td>P5</td>
<td>1</td>
<td>0.1804</td>
</tr>
<tr>
<td>m6</td>
<td>1</td>
<td>0.3161</td>
</tr>
<tr>
<td>M6</td>
<td>1</td>
<td>0.2504</td>
</tr>
<tr>
<td>m7</td>
<td>2</td>
<td>0.4196</td>
</tr>
<tr>
<td>M7</td>
<td>3</td>
<td>0.5950</td>
</tr>
<tr>
<td>P8</td>
<td>1</td>
<td>0.1125</td>
</tr>
<tr>
<td>m9</td>
<td>3</td>
<td>0.7618</td>
</tr>
<tr>
<td>M9</td>
<td>2</td>
<td>0.5382</td>
</tr>
<tr>
<td>m10</td>
<td>1</td>
<td>0.3714</td>
</tr>
<tr>
<td>M10</td>
<td>1</td>
<td>0.1936</td>
</tr>
</tbody>
</table>

Figure 4: Dissonance ratings for triads.
Table 3: Mean rated dissonance and Krenek’s category for triads. The categories are 1: Three consonances; 2: Two consonances and one mild dissonance; 3: One consonance and two mild dissonances; 4: Two consonances and one sharp dissonance; 5: One consonance, one mild and one sharp dissonance; 6: One mild and two sharp dissonances.

<table>
<thead>
<tr>
<th>Dyads</th>
<th>Category</th>
<th>Dissonance</th>
<th>Dyads</th>
<th>Category</th>
<th>Dissonance</th>
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<tr>
<td>M₃,m₃,P₅</td>
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<td>M₃,P₅,M₇</td>
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<tr>
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<tr>
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<tr>
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<tr>
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<td>m₂,m₂,M₂</td>
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<tr>
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Discussion/conclusion

A web-based listening test was devised in which participants rated the perceived dissonance of 46 dyads and triads. Each example was presented twice, with one example shifted a fifth up. This gave a total of 92 examples. A relatively high Cronbach’s alpha for dyads and triads, as well as the combination of the two, indicates that the inter-rater reliability is good. Most participants agreed on which dyads and triads that was dissonant and which were not. It can thus be assumed that dissonance is usable as a perceptual feature in future studies.

For dyads, dissonance ratings were as expected with the minor second rated as most dissonant. The minor ninth was rated as second most dissonant, followed by the major second and the major seventh. The tritone and minor seventh received about the same ratings, just slightly less dissonant than the abovementioned dyads. According to Krenek, the tritone could be regarded as neutral but in this context it is evident that it fits in the category of mild dissonances. It is evident from these results that
categorical models such as Krenek’s have some drawbacks. The differences between categories are somewhat small and for the consonant dyads, there is a need for further division (such as perfect and imperfect consonances). One interesting observation is that the minor ninth were regarded as more dissonant than major seventh, despite the fact that they both are an octave above ± a minor second. A possible explanation of this may be the prevalence of major seventh chords in western music. Furthermore, the perfect fourth was not significantly less dissonant than the major third, and as we see in figure 2, the case is almost the same for the perfect fifth. Unison and octave are unambiguously the most consonant dyads.

Major and minor triads contain the same dyads but there is a slight difference in the ratings. This may be accounted to the convention that minor triads convey tension. Krenek’s categories don’t fit very well for triads. There seems to be a lot of variation that can’t be directly accounted to how dissonant the containing dyads are. There are, however some obvious cases such as m2,m2,M2, which is unambiguously the most dissonant triad. All triads containing a sharp dissonant dyad received a high dissonant rating. There is an exception for this in cases M3,P5,M7 and P5,M3,M7. These contain one sharp dissonance, which should indicate an overall high dissonance rating. But these triads both resemble the major seventh chord but with one note missing. And just as the major seventh is recognised as being less dissonant than for example the minor ninth the entire triad is recognised as a somewhat consonant. Alternatively, the presence of a fifth in these chords may stabilise them. Thus, there was a clear effect that could be attributed to musical practice.

The rating scale with fixed ends may have led to a truncated distribution of the ratings. This is assumed to be because participants put a lot of dyads and triads at “not dissonant at all” and at “completely dissonant” even though they were different. By using different scaling such as the centiMax scale (Borg & Borg, 2002), which allows the rater to exceed maxima/minima on the scale this could be adjusted. Some of these problems might also have been caused by the use of a web-based survey. Web-based surveys allow easier recruiting procedures but removes control. A more controlled environment would also allow more proper training of the participants.

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References


