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JASA ARTICLE

Pleasantness of nonlinear distortion in isolated triads of synthetic timbre

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ABSTRACT:
Distortion of sound is an important tool to increase the variety of timbres in musical compositions, but perceived pleasantness of distortion is understudied, and studies are limited to guitar practices in rock and metal music. This study applied a more systematic approach, using synthetic timbre and creating an audio-plugin that realized nonlinear symmetric and asymmetric distortion. Participants evaluated the perceived pleasantness of isolated triads differing in distortion (undistorted, symmetric, asymmetric), tonality (minor, major), and position (low, high, wide), taking baseline differences of tonality and position into account. Perceived pleasantness decreased by distortion, and the decrease was stronger for minor than major triads and stronger for asymmetric than symmetric distortion. Position played only a minor role in the evaluations, except for stimuli in high positions. Stimulus-based analyses showed a relation between pleasantness and the variability of roughness, mean spectral centroid, and mean sound intensity. Subject-based analyses revealed a smaller decrease in pleasantness with a preference for electronic music. Importantly, some distorted triads were rated as pleasant in absolute terms: major triads with symmetric distortion in low or wide position. That is, indeed, distortion is not always categorized as unpleasant but can be perceived as pleasant.

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I. INTRODUCTION

Acoustic distortion is an important compositional feature in electronic music and is utilized in various ways by musicians as well as engineers to achieve timbre variations of both subtle and drastic dimensions (Dutilleux and Zölzer, 2002; Rice, 2020). Investigating the pleasantness of distortion might be counterintuitive at first sight. In the field of electroacoustics, the linearity of sound transmission in equipment like preamplifiers or loudspeakers is highly desirable. Nonlinear distortion is regarded as a disturbance and flaw, which needs to be diminished as much as possible. However, common verbal descriptors of the distortion of guitar sounds by effect pedals span adjectives such as "warm," "smooth," "full," and "creamy" on the one hand and "dirty," "noisy," and "fizzy" on the other (Rice, 2020), demonstrating the broad range of timbral perception that can be achieved through distortion. Importantly, distortion has grown beyond musical instruments and styles that traditionally made use of it, like electric guitar and rock and heavy metal music (Rice, 2020). However, experimental research on the perception of distortion is rare and mainly based on the electric guitar timbre (Herbst, 2017, 2019; Marui and Martens, 2005; Rice, 2020). The focus of our study is to extend the knowledge on the perception of distortion, particularly its perceived pleasantness, and to give a more general rather than style-specific and guitar-based insight into the perception of isolated distorted triads (that is, a sound consisting of three fundamental frequencies/tones). We systematically manipulated different types of distortion on major and minor triads in different chord positions using two synthetic instrument timbres of varying spectral complexity.

A. Characteristics of distortion

Distortion as a stylistic device has been explored by composers and musicians for decades. One early composed example is the cadence for horn in Carl Maria von Webern's Horn Concertino op. 45 (1815), in which multiphonics are produced by playing one note and humming another. Later, this type of distortion technique was prominent in jazz (e.g., John Coltrane, Evan Parker). Composers like Stockhausen and Maxwell Davies applied ring modulation in the 1960s onto the microphone input of different instruments and the singing voice. Distortion techniques were further promoted by developments in audio signal amplification (Dutilleux and Zölzer, 2002; Zollner, 2014). Vacuum tubes inevitably add an amplification-level-dependent number of distortion products to the amplified signal (Hartmann, 2013; Zollner, 2014). This technical flaw was soon discovered and exploited in popular music; particularly, electric guitarists

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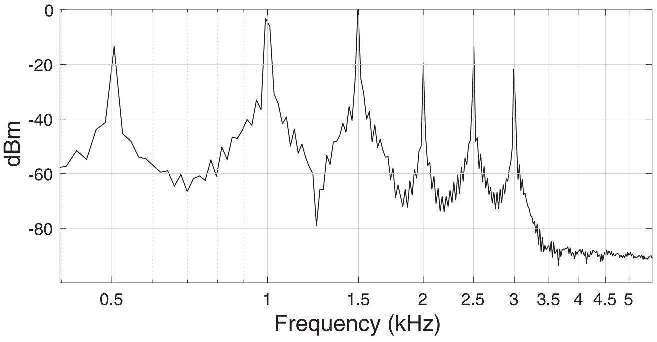

FIG. 1. Spectrum of two sinuses at 1 and 1.5 kHz distorted asymmetrically with second-order polynomic distortion.

made use of the expressive potential of distortion from the 1950s (Barbour, 1998). By overdriving guitar amplifiers far beyond their "sweet spots" within which these were designed to operate to keep distortion products as low as possible, a more assertive timbre was achieved (Barbour, 1998; Rice, 2020). This trend led manufacturers to explicitly design their amplifiers to distort input signals in controllable ways by chaining multiple vacuum tubes in a row (Barbour, 1998; Dutilleux and Zölzer, 2002; Zollner, 2019).

Technically, distortion can be defined in a very simple way: "A signal processing system generates distortion if the waveform coming out of the system does not have exactly the same shape as the waveform going into the system" (Hartmann, 2013). Distortion in this sense means the alteration of the spectral composition of a signal. When the only alteration of a distorted signal is its volume or the volume of its spectral components, the distortion is called linear. The more common use of the term distortion is in a nonlinear sense, implying harmonic and intermodulation distortion (Dutilleux and Zölzer, 2002; Hartmann, 2013; Müller, 2015). Harmonic distortion relates to the resulting spectral components in nonlinearly distorted signals that are multiples of the input frequency and are called harmonics (e.g., the fundamental frequency is the first harmonic; the octave, which is twice the fundamental frequency, is the second harmonic, etc.; Müller, 2015). Intermodulation distortion becomes observable in the form of combination tones, when—as most of the time—the input signal comprises more than a single sinus (Hartmann, 2013; Parncutt, 1989; Smoorenburg, 1972). These so-called difference or summation tones occur at the difference or sum frequency of the input signal partials and are not integer-valued multiples and, therefore, inharmonic partials of the resulting signal. With increased distortion, more harmonics and combination tones appear in the output signal (Reiss and McPherson, 2015; Zollner, 2014). The timbre of distortion is described to create a more "heavy" (Berger and Fales, 2004) or "thick" sound (Walser, 1995), mirroring the fact that, indeed, nonlinear distortion adds something (e.g., weight, volume, density) by adding harmonics and combination tones.

Figure 1 depicts a distorted sound based on the input signal of two sinuses, one with a frequency of 1 kHz and the other 1.5 kHz, as can be seen by amplitude peaks at 1 and 1.5 kHz. This signal yields the musical fifth, a particularly important interval in metal and rock for distorted guitar sounds, which we will return to later. The input signal was distorted asymmetrically, resulting in (i) harmonics, i.e., at 2 and 3 kHz, and (ii) combination tones at 0.5 and 2.5 kHz.

The characteristic curve of distortion shows the relation between sound input and output level (Fig. 2) and can have a symmetric or asymmetric shape. Asymmetric distortion produces integer-valued harmonics, while symmetric distortion produces odd-ordered harmonics. Both additionally produce intermodulation products (Hartmann, 2013; Zollner, 2019). Polynomic distortion is often applied in digital systems [but see other ways of digitally controlled distortion in D'Angelo *et al.* (2013) and Dutilleux and Zölzer (2002)]. It describes a subset of characteristic curves that can be described by a polynomial function. The higher the order of the polynomial, the more harmonics and combination tones appear in the distorted output signal (compare Figs. 1 and 3). The order and number of harmonic and inharmonic (combination tones) distortion products vary tremendously for different characteristic curves (Dutilleux and Zölzer, 2002; Zollner, 2019).

In the current study, we first built a digital interface that can be used to apply symmetric and asymmetric distortion to any sound signal (Chemnitz, 2022). That is, the digital interface enabled us to extend earlier research on the distortion of the guitar (Herbst, 2017; Rice, 2020) to other timbres

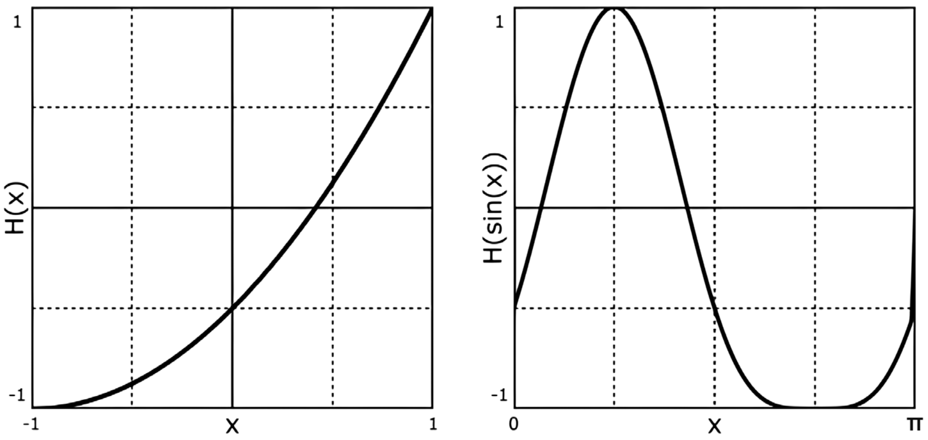

FIG. 2. Example of an asymmetric characteristic curve with second-order polynomial (left, input level on the x axis) of a distorting system and the waveform of a distorted sinus (right, phase on the x axis).

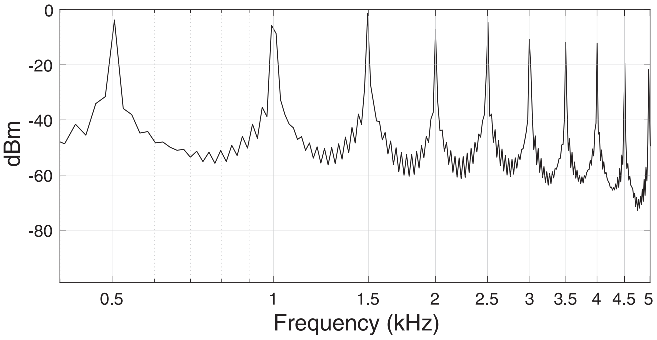

FIG. 3. Spectrum of two sinuses at 1 and 1.5 kHz distorted asymmetrically with fourth-order polynomic distortion.

and to specify distortion by its polynomial function as well as to make the stimulus material—particularly the applied distortion—easily reproducible, instead of referring to commercially distributed distortion tools, such as guitar pedals (Walser, 1995; Rice, 2020).

B. Distortion in heavy metal music: The power chord

In heavy metal and rock music, distortion of the electric guitar is one of the most characteristic elements of this style (Lilja, 2009, 2015; Walser, 1995), and research on distortion as a timbral feature is mostly on guitar sounds (Herbst, 2017, 2019; Lilja, 2009, 2015; Marui and Martens, 2005; Rice, 2020). The preference for distortion within these styles is related to the characteristic use of musical features like the power chord (Lilja, 2009; Walser, 1995), which is the simultaneously played fifth, as well as to the development of guitar amplifiers with characteristic sound features (Rice, 2020; Walser, 1995). The perception of distortion products has been investigated mainly by means of the power chord in listening experiments (e.g., Herbst, 2019; Juchniewicz and Silverman, 2013). As the power chord does not include the third, it is open to be interpreted as minor or major. Interestingly, distorted power chords were interpreted as being major instead of neutral. The distorted power chord was perceived as more major than the undistorted power chord (Juchniewicz and Silverman, 2013). This might not be surprising, as the major third is the fourth overtone and the minor only the sixth. In fact, it has been argued that the distorted power chord includes the major third as harmonic, increasing the similarity in the overtone spectrum of distorted power and major chords (Herbst, 2017; Lilja, 2015).

Despite its similarity, the undistorted major can be well distinguished from the distorted power chord. The sudden occurrence of the undistorted major in a sequence of distorted power chords is coded in the brain (Virtala *et al.*, 2018), shown by the elicitation of specific components in the event-related potential, such as the mismatch negativity (MMN) and a positivity (P3). The change detection occurs as early as 100–250 ms (MMN) or 200–350 ms (P3) after the onset of the deviating sound. The MMN indicates that the deviating sound is automatically detected, and the P3 indicates attentional processing. Likewise, distortion (deviant triad or power chord) is coded in the brain (Virtala *et al.*, 2018).

C. Consonance and pleasantness of triads

Perceived pleasantness is highly related to perceived consonance, and therefore, a second line of research related to our study is on perceived consonance. Non-musicians use the terms rather synonymously, while musicians differentiate between the music-specific terms consonance-dissonance, and pleasant-unpleasant [Arthurs *et al.*, 2018; see Terhardt (1984) for definitions of consonance]. In experimental designs, perception of consonance has been operationalized by measuring perceived pleasantness (e.g., Johnson-Laird *et al.*, 2012). The term consonant defines a quality of simultaneous or successive sounds, and we concentrate here on simultaneous consonance. Its perception is crucially related to the harmonicity of the sound (e.g., high overlap of the overtone spectrum of the combined tones) and the interference between the composed tones as well as cultural aspects like familiarity with harmonicities [see Harrison and Pearce (2020) for a review; Marijeh *et al.*, 2023]. Interference occurs between neighboring partials that produce beating, i.e., amplitude fluctuations that can be perceived as rough and harsh. Consequently, simultaneous intervals with fractions as simple as 1:1 (unison), 2:1 (octave), and 3:2 (fifth) are considered consonant, whereas more complex fractions like 9:8 and 16:15 (major and minor second) are considered dissonant (Plomp and Levelt, 1965).

Research on the experience of consonance, pleasantness, and stability of triads shows overlapping results. Minor triads were perceived as less consonant than major triads (Arthurs *et al.*, 2018; Lahdelma and Eerola, 2016), less pleasant (Herbst, 2017; Johnson-Laird *et al.*, 2012), and less stable (Arthurs *et al.*, 2018; Lahdelma and Eerola, 2016). However, preference did not differ between minor and major modes (Lahdelma and Eerola, 2016). Interestingly, the minor triads were rated less positive in terms of valence than major triads (Lahdelma and Eerola, 2016), but this affective distinction is opposite for a group of listeners from Pakistan (Lahdelma *et al.*, 2021), showing the strong influence of cultural familiarity on chord perception. In addition, even within Western culture, familiarity (e.g., counts of chords in musical corpora) contributes strongly to perceived consonance (Eerola and Lahdelma, 2021), and musical sophistication increases pleasantness ratings of triads (Smit *et al.*, 2019). Also, timbre can contribute to the perception of consonance [Arthurs *et al.*, 2018; but see Parncutt *et al.* (2023) and Friedman *et al.* (2021)] as well as register (Lahdelma and Eerola, 2016). Triads in higher register were perceived as less consonant and positive and were less preferred than in lower register.

D. Perceived pleasantness of distorted major and minor triads

Studies on consonance and pleasantness of distorted major and minor chords are still in their beginnings.

Empirical studies on distortion focus on metal and rock music, guitar timbres, and genre-specific distortion tools (i.e., guitar pedals or amplifiers from specific companies; Herbst, 2019; Rice, 2020). They are often descriptive, lacking statistical backup (e.g., Berger and Fales, 2004; Herbst, 2017; Lilja, 2015; Rice, 2020) or are directed to other research topics, such as the expressions and qualities (Marui and Martens, 2005; Rice, 2020) or the acoustic properties of perceived distortion (Lilja, 2015) or how musical developments (chord structures and progressions) might be related to the increased performance practice of distortion (Lilja, 2009). For example, Lilja (2009) reports that in heavy metal music, distorted minor triads are rare and that this might relate to being perceived as rougher and more dissonant than distorted major or power chords. Berger and Fales (2004) as well as Rice (2020) assume that perception of distortion is systematically related to the acoustic properties of the amplifier, such as altering brightness, roughness, spectral flux, and spectral centroid of the sound. In fact, different types of nonlinear distortion were distinguishable by the semantic dimensions dark-bright, sharp-dull, and thin-thick (Marui and Martens, 2005).

To our knowledge, only one study (Herbst, 2019) is directed to perceived pleasantness of distortion. The results of this study indicate that distortion decreases mean pleasantness ratings and that this decrease was stronger for the minor triad than the major triad or power chord. Pleasantness ratings correlated positively with the preference for listening to rock music, as some enthusiasts of rock did not show a decrease in pleasantness by distortion. Pleasantness was negatively correlated to acoustic features such as roughness, spectral flux, spectral centroid (sharpness), and loudness (Herbst, 2019). However, we think that the study of Herbst (2019) needs replication, as parts of the methods and statistical analyses are difficult to interpret,[1] and generally replications are desirable given the replication crisis in science (Wiggins and Christopherson, 2019).

Our study differs from earlier studies in several aspects. One crucial difference is our decision to move the research context from distortion of guitar sounds to a less style-specific timbre and easily reproducible stimulus material. We used static synthesizer timbres and systematically manipulated distortion parameters. To do so, we built an audio-effect plugin for use in a digital audio workstation (Chemnitz, 2022). This plugin enabled the manipulation of two key features of distortion: (i) the order of the polynomial of the characteristic curve and (ii) the symmetry of the characteristic curve that is the amount and type of distortion (e.g., symmetric, asymmetric). We predicted that perceived pleasantness will decrease with increased complexity of distortion, analogous to the manipulation of overdrive and distortion (Herbst, 2019). Given that our evaluations ranged from "very unpleasant" to "very pleasant," we can also explore whether some of the distorted stimuli were rated as overall pleasant, even if they were rated as less pleasant than the undistorted stimuli. Regarding tonality, we expect that major triads will be perceived as more pleasant when distorted than minor triads (Lilja, 2009, 2015).

Given the literature on perceived consonance (e.g., Lahdelma and Eerola, 2016; Eerola and Lahdelma, 2021), we included register as a factor in our design (low, high, and wide position as a mixture of low and high). Interestingly, low position has been perceived as more consonant and positive and was preferred more than high position (Lahdelma and Eerola, 2016), but the interferences between partials increase with lower frequencies (Harrison and Pearce, 2020). This raises the question of whether pleasantness of distorted sound interacts with position (and/or tonality). The factor position has not been included in research on distortion so far. Hence, our study is the first taking this factor orthogonally into account.

In addition, we included several measures related to music experiences and familiarity. The underlying reasoning is that the perceived pleasantness might be less affected by distortion if participants are more sophisticated or familiar with distorted sounds or related music. For undistorted triads, familiarity had a positive impact on perceived consonance (Eerola and Lahdelma, 2021) and changed perceived valence for listeners with different cultural backgrounds (Lahdelma *et al.*, 2021). Musical sophistication increased perceived pleasantness (Smit *et al.*, 2019). To measure experience with distorted music, we asked participants how often they listen to music that includes distortion on a seven-point rating scale (1 = "very rarely"; 7 = "very often"). To measure musical sophistication, we applied the sophistication subscale of the Goldsmiths Musical Sophistication Index (Gold-MSI; Müllensiefen *et al.*, 2014). The Gold-MSI is a short self-report inventory, independent of musical preferences, capturing the multi-dimensionality of musical behaviors and skills. As a measure of familiarity with certain kinds of musical styles, we selected music preferences of four items from the STOMP (Rentfrow and Gosling, 2003): metal, rock, electro, and classical. Prior research showed a relation of perceiving distortion as pleasant and being an enthusiast of metal or rock music (Herbst, 2019). Different from that study, we used synthesizer timbres and not guitar stimuli. Therefore, we also included the style electro, the compositions of which include distorted synthesizer sounds. We also explored a relation to classical, although predictions are less clear. Listeners of contemporary classical music will be experienced with distorted synthesizer sounds, but traditional listeners of classical music might dislike distorted sounds similarly to noises in the tone production. Hence, listeners of classical music might show a positive or a negative effect.

Last, we analyzed the acoustic features of our stimuli and related them to the pleasantness ratings. Selection of features is complicated by the fact that many acoustic features are highly correlated (e.g., Lange and Frieler, 2018). We based our selection on the literature of distorted guitar sounds (e.g., Herbst, 2019; Rice, 2020) and selected the features roughness, spectral centroid, spectral flux, inharmonicity, and loudness (amplitude envelope). These features define sensory pleasantness (Fastl and Zwicker, 2007) and are important for auditory perception of undistorted sounds.

Roughness has been regarded as the key feature for perceived consonance or pleasantness for decades [for reviews, see Di Stefano and Spence (2022) and Di Stefano *et al.* (2022)]. Both roughness (interference) and harmonicity together predict consonance or pleasantness judgments of undistorted sounds (Eerola and Lahdelma, 2021; Friedman *et al.*, 2021; Marijeh *et al.*, 2023; Parncutt *et al.*, 2023). Spectral centroid (Eerola and Lahdelma, 2021) or mean pitch height (Smit *et al.*, 2019) contributes further to consonance predictions. Hence, our selection of features captures broadly what should be relevant for the evaluation of distorted triads. Note that we included two timbres of different spectral complexity to increase variance in our stimulus set.

II. METHOD

A. Participants

A listening test was conducted with 84 participants. The average age was 23.5 years (range 18–35; 32 women, 52 men), and 64 were students (24 from a music-related subject, six from psychology). The average musical sophistication (Gold-MSI) was mean (*M*) = 90 [standard deviation (*SD*) = 20, range = 42–116]. This is slightly higher than the published norm data with *M* = 81.58, *SD* = 20.62, range = 18–126 (Müllensiefen *et al.*, 2013). Note that due to technical failure, two items of the 18-item scale were not recorded and have been replaced by the individual means for these measures. For compatibility with other studies, we report this adjusted mean. Individual familiarity with distortion was evaluated using a seven-point scale and resulted in *M* = 4.74 (*SD* = 1.72), which is higher than the mid-point of the scale. That is, the majority of participants were rather familiar with distortion. Musical preferences of the participants were recorded by the STOMP (Rentfrow and Gosling, 2003), resulting in left-skewed distribution for styles like classical, jazz, blues, alternative, rock, pop, soundtrack, rap, soul, and electro, whereas religious and country were more right-skewed and not liked, and the distribution of the other styles was more equal (metal) or normal around the mean (folk).

Participants were invited to take part in the study via email and online forums. The experiment took place over a time span of two weeks in June 2021. There was no payment or reward involved. The experiment lasted 15–30 min. Participants gave written informed consent by mouse click before the experiment started. All experimental procedures were approved by the Ethics Council of the Max Planck Society.

B. Apparatus

Data were assessed by using the audio evaluation service SenseLab online (https://forcetechnology.com). Participants were asked to use headphones or high-quality loudspeakers and to ensure a rather quiet environment. Given an example trial, participants chose their preferred volume in the beginning of the experiment based on a sample of white noise normalized to the same perceived loudness as all of the stimuli (using the AudioToolbox "acousticLoudness" function in MATLAB) and were instructed to not change the loudness level during the experiment.

C. Stimuli and materials

Triads occurred in major and minor tonality and in three different "positions": "low" (close) = root position on C4; "high" (close) = root position on C5; "wide" (spread) = sixth chord on E4/E-flat4 with fifth in the upper voice (see Fig. 4). We applied distortion with polynomials of the third order, because starting with fourth-order polynomials, pitches can hardly be perceived. The three conditions of distortion were (i) undistorted, (ii) cubically distorted with a symmetric curve, or (iii) asymmetric characteristic curve. We will explain in detail the distorting system below. To summarize, stimuli were manipulated by three factors of different levels: tonality (two), position (three), and distortion (three). To increase variance in the stimulus material, we used two different timbres: a triangle wave and a sine wave frequency-modulated at two, three, and four times the fundamental frequencies. This resulted in overall 36 different stimuli, each of a duration of 5 s. The synthesizer timbres had static settings and were faded in and out in 10 ms. All stimuli were rendered in Ableton Live 10 using the frequency modulation (FM) synthesizer plugin "Operator," using an equal tempered tuning system. Finally, the stimuli were rendered as 16 bit wave files and normalized using the "acousticLoudness" function in MATLAB. Evaluation of the pleasantness (German: "Wohlklang," an expression describing acoustic qualities as well as the subjective experience of it) of the stimuli was by a nine-point rating scale, with five verbal labels arranged vertically from bottom to top: "very unpleasant," "rather unpleasant," "neither nor," "rather pleasant," "very pleasant," and four additional marks in between the labels, resulting in nine levels to choose from, coded in the analyses as integers from 1 ("very unpleasant") to 9 ("very pleasant"). Stimuli and data are available at https://osf.io/hjt79/.

D. The audio-plugin SAUND—Symmetric and asymmetric unit for nonlinear distortion

To have transparent control over the coefficients of the polynomial distortion and, thereby, the characteristic curve, a VST 3 plugin was programmed by the authors L.C. and F.B. (https://github.com/leonchemnitz/SAUND; Chemnitz,
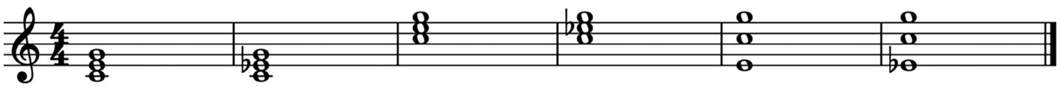
FIG. 4. Stimuli were based on six different triads (two tonalities and three positions).

2022). The VST 3 specification (Grabit, 2022) allows the software to be integrated into most state-of-the-art digital audio workstations (DAW) and audio processing tools. Importantly, this system does not include additional filters, which are otherwise highly common but would adulterate the resulting output in an undocumented way. For usage outside this experiment, the tool has the benefit of depicting the characteristic curve as well as an accordingly distorted sinus, which visualizes the distortion in an intuitive and precise way (see supplemental Fig. S1).[2]

Polynomial distortion in SAUND is defined by two equations [Eqs. (1) and (2)] calculating the transfer functions H_{asym} and H_{sym}. Both equations are parameterized with coefficients $a_n \in \mathbb{R}$ and $b_n \in \mathbb{R}$, with $n \in \mathbb{N}_0$, respectively. The coefficients serve the dual purpose of scaling their associated monomial (e.g., a_5 scales x^5) and the entire polynomial by their cumulative sum. The latter effectively normalizes the output of the function. This was added for convenience so that audio levels remain approximately unchanged while the coefficients are manipulated. $N \in \mathbb{N}_0$ denotes the maximal order of the polynomial. In the current implementation of SAUND, $N = 8$ for symmetric as well as asymmetric distortion. By convention, digital audio levels are in the range of [–1; 1]. However, for polynomial distortion to work properly, the input needs to be non-negative and preferably in the range of [0; 1]. This is because otherwise, the even ordered monomials would flip the sign of the input from negative to positive, yielding unwanted results. To bring the signal into the desired range, it is offset and scaled at the input and invertedly scaled and offset at the output:

$$H_{asym}(x) = 2\left(\frac{\sum_{n=0}^{N} a_n \left(\frac{x+1}{2}\right)^n}{\sum_{n=0}^{N} a_n}\right) - 1. \tag{1}$$

To achieve symmetric distortion, H_{sym} is defined as a piecewise function. As with asymmetric distortion, the signal is offset by 1 at the input and in the case of a positive signal also scaled by –1. This scaling and offset are again undone at the output:

$$H_{sym}(x) = \begin{cases} \dfrac{\sum_{n=0}^{N} b_n (x+1)^n - 1}{\sum_{n=0}^{N} b_n} & \text{if} \quad x < 0 \\ -\left(\dfrac{\sum_{n=0}^{N} b_n (1-x)^n}{\sum_{n=0}^{N} b_n} - 1\right) & \text{if} \quad x \geq 0. \end{cases} \tag{2}$$

The graphical user interface of SAUND consists of two rows of eight faders, one row controlling the asymmetrical amount of distortion and the other the symmetrical. For each fader, the user can select values within the range [0; 1] with a resolution of 0.01. In our experiment, the symmetrically distorted stimulus was generated by applying the coefficient $b_3 = 1$ in the polynomial, and the asymmetrically distorted one by $a_3 = 1$. All other coefficients were scaled to zero.

E. Procedure

Each stimulus was presented three times, resulting in 108 evaluations. The serial order of the 36 stimuli of one set was randomized for each participant and every run. Every stimulus was evaluated on a single display. Participants initiated the start of the audio file by mouse click. The stimulus was looped with a short silence of 200 ms in between until the evaluation was given by mouse click, upon which the display for the next stimulus appeared. Participants were reminded every 5 min to take a short break. They continued self-paced.

F. Data treatment

We used IBM SPSS version 25 (SPSS, Chicago, IL) for statistical analysis. Tests were two-tailed, and the α level was set to 0.05. We applied the Greenhouse–Geisser epsilon for non-sphericity (GG) wherever necessary. For *post hoc* analyses, we applied the Bonferroni correction (if not stated otherwise).

We will report several analyses. First, we asked whether distortion is the only driving factor to differentiate between pleasant and unpleasant sounds. As the mid-point of the bipolar scale was 5, this value differentiates between (more or less) pleasant and (more or less) unpleasant. If distortion is unpleasant but undistorted sounds not, mean pleasantness of all distorted stimuli should be below 5, and that of all undistorted stimuli should be above 5. Statistically, we tested this by one-sample *t*-tests of mean pleasantness against the value 5.

Second, we calculated the effect of distortion, taking into account the baseline ratings of the undistorted stimuli that differed in tonality and position. That is, we built difference scores between the mean evaluations of the undistorted stimuli and each of the two types of distorted stimuli (asymmetric/symmetric) for different tonalities and positions (subtraction of mean pleasantness of distorted from undistorted stimuli). The results of the difference scores refer to the decreased effect of distortion on pleasantness based on what can be expected given baseline effects of tonality and position on perceived pleasantness. We fitted these difference scores into a three-factorial ANOVA, with the three-level factor position, the two-level factor tonality, and the two-level factor distortion (for an ANOVA fitting the raw means and not the difference scores, see supplementary materials).[2]

Third, we analyzed individual differences of the sensitivity for distortion between participants by correlational analyses. We related the individual mean distortion effect (difference scores) with measures of interest, such as self-rated familiarity with distorted music, musical sophistication, and music preference for metal, rock, electro, and classical. To reduce the complexity of the design, we aggregated the data for the main factor of distortion but neglected the factors tonality and position. This resulted in only two difference scores per participant, estimating the effects of asymmetric and symmetric distortion across tonalities and positions.

Fourth, we related acoustic features of each stimulus to its mean pleasantness ratings, including all stimuli, also the undistorted ones. The features were amplitude envelope, roughness, spectral centroid, spectral flux, and inharmonicity, extracted by MIRtoolbox (version 1.7.2; Lartillot and Toiviainen, 2007). Before analyses, we excluded the fade-in and fade-out sections of each wav file to increase precision of the measure and avoid confounds (i.e., mean spectral flux is affected by fade-in/fade-out). For all but inharmonicity (which calculates the number of partials that are not multiples of the fundamental frequency), we analyzed *M* and *SD* as a measure of variability, based on a frame composition with default settings (50 ms window size, half overlapping). Unfortunately, the feature roughness correlated with the amplitude envelope, $rho(34) = 0.403$, $p = 0.007$, which was an unforeseeable confound, likely related to the type of stimuli we used (simultaneously presented triads, and not music unfolding in time) in relation to the way roughness is calculated in MIRtoolbox. To capture the feature roughness, nevertheless, we normalized the amplitude of the stimuli to be on the same root mean square (rms) and repeated the calculation of roughness. This should ideally leave us with estimates of roughness that exclude the variance due to changes in mean amplitude.

All reported correlations were based on Spearman's *rho* to take into account differences in the scales of the measurements.

III. RESULTS

A. Is distortion generally perceived as unpleasant?

The factor distortion did not split pleasantness ratings in two parts, such as distorted sounds being perceived as unpleasant and undistorted as pleasant. Rather, a mixed pattern occurred (Fig. 5). Most asymmetrically distorted sounds were perceived as unpleasant, and undistorted sounds in low and wide positions were perceived as pleasant. However, symmetrically distorted major triads were perceived as pleasant in low, $t(83) = 5.23$, $p < 0.001$, as well as wide position, $t(83) = 4.03$, $p < 0.001$. That is, distorted sounds are not *ipso facto* unpleasant but can be pleasant. In addition, some stimuli were perceived as indifferent: Undistorted minor and major triads in high position were not perceived as pleasant, both t's < 1, and asymmetric major triads in low position were not perceived as unpleasant, $t < 1$.

B. Does distortion decrease perceived pleasantness, and if so, is this effect affected by position and tonality?

We now asked about the relative effect of distortion on pleasantness, taking evaluations of the undistorted stimuli as a baseline. This is important, as even undistorted stimuli showed effects of position and tonality. Indeed, perceived pleasantness of undistorted triads decreased from low to high position and from major to minor tonality for the undistorted stimuli (see supplementary materials[2] for a two-factor ANOVA on the ratings for undistorted stimuli). However, is the relative effect of distortion modulated by position and tonality above what can be expected from undistorted stimuli? The results from the three-factor ANOVA on the difference scores were complex. Interestingly, taking baseline differences into account, the main effect position was not significant, $F(1.7, 140.1) = 2.43$, $p = 0.101$, $\eta_p^2 = 0.028$ (GG), as well as its interaction with tonality, $F(2, 166) = 1.91$, $p = 0.153$, $\eta_p{}^2 = 0.023$. That is, some of the variance of position and its interaction with tonality for evaluations of distorted mean evaluations seen in Fig. 5 was explained by the basic effects on undistorted stimuli. Importantly, all other main effects and interactions were significant. More specifically, the ANOVA resulted in main effects of tonality, $F(1, 83) = 44.67$, $p < 0.001$, $\eta^2 = 0.350$, and distortion, $F(1, 83) = 65.99$, $p < 0.001$, $\eta^2 = 0.443$; an interaction of tonality and distortion, $F(1, 83) = 10.77$, $p = 0.002$, $\eta^2 = 0.115$; an interaction of position and distortion, $F(2, 166) = 7.91$, $p = 0.001$, $\eta_p^2 = 0.087$; and a three-way interaction, $F(2, 166) = 7.57$, $p = 0.001$, $\eta_p^2 = 0.084$.

The general pattern is depicted in Fig. 6. All mean difference scores were clearly above zero, that is, (i)

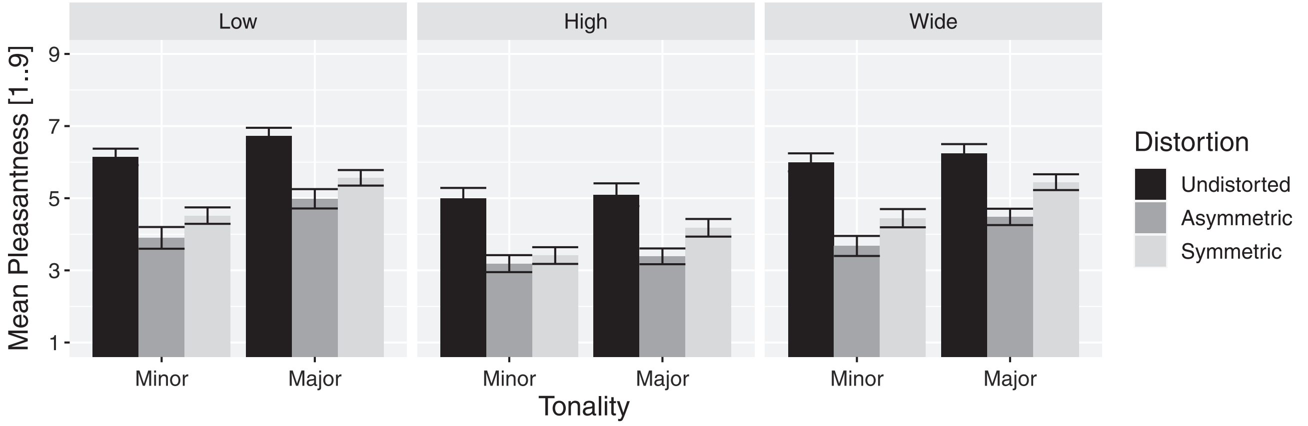

FIG. 5. Means and confidence intervals of perceived pleasantness for stimuli differing in tonality, distortion, and position.

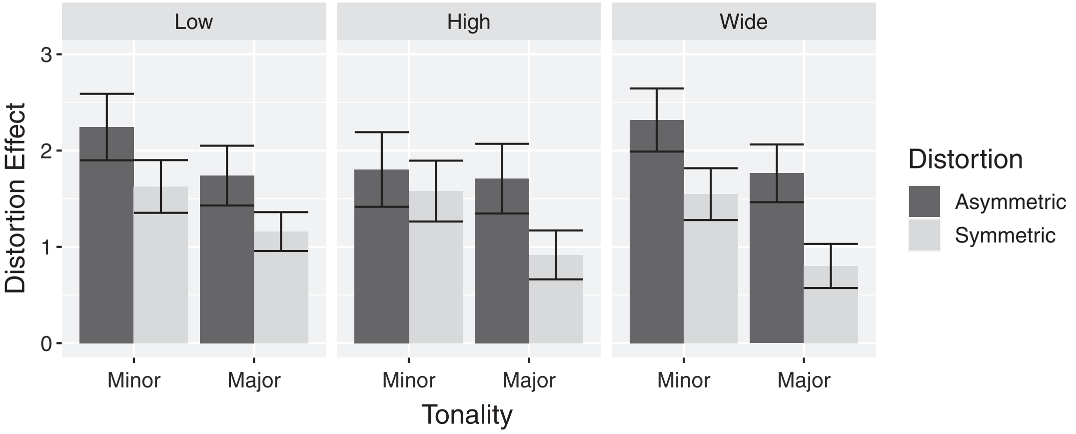

FIG. 6. The distortion effect for low, high, and wide register, minor and major tonalities, and two types of distortion.

undistorted stimuli were perceived as more pleasant than distorted. The significant main effects indicate that (ii) major triads ($M = 1.27$, $SD = 1.02$) were affected less by distortion than minor ($M = 1.85$, $SD = 1.27$), and (iii) symmetric distortion ($M = 1.27$, $SD = 0.94$) affected ratings less than asymmetric ($M = 1.93$, $SD = 1.35$). However, the main effects were modulated by interactions, showing that there were exceptions to the general pattern of (ii) and (iii). The pattern changed particularly for the triads in high positions. The distortion effect did not differ between major and minor for high asymmetric triads, $t(83) < 1$. For high minor triads, there was no difference between asymmetric and symmetric distortion, $t(83) = 1.99$, $p > 0.05$. Note that the missing main effect of position is mirrored by *post hoc* comparisons for the major triads with asymmetric distortion and the minor triads with symmetric distortion. Comparing each of the three positions pairwise resulted in t's < 1.

C. Is the distortion effect affected by self-rated familiarity with distorted music, music sophistication, or music preference?

In contrast to our predictions, neither familiarity with distorted music nor musical sophistication correlated with the reduction of the distortion effect on pleasantness (see Table I). However, the effects of asymmetric and symmetric distortion on pleasantness were smaller, with higher preference for electronic music. In addition, participants preferring classical music showed an increased effect of asymmetric distortion on pleasantness. Different from the study on distorted guitar sounds (Herbst, 2019), preference for metal and rock was not associated with a pleasurable experience of distortion.

D. Is perceived pleasantness related to acoustic features of the stimuli?

Table II lists correlation coefficients between stimulus-based mean ratings and acoustic features. In addition, Fig. 7 depicts selected bi-variate correlations and visualizes as a third potential influence position and distortion type by color coding. Analyses of potential contributions are not included due to the low number of cases. The top row includes histograms for the mean pleasantness ratings split by position and distortion. The factor position was less uniquely related to pleasantness (the distributions overlap strongly) than the factor distortion (less overlap), with the asymmetrically distorted stimuli being perceived as less pleasant, undistorted as more pleasant, and symmetrically distorted in between. See also Table III, reporting mean feature values split for distortion.

The analyses of the acoustic features show some correlations with pleasantness. Sound intensity (mean amplitude envelope) correlated positively with pleasantness. The higher the intensity, the more pleasant a sound was. The effect was slightly affected by position or distortion (Fig. 7, second row). A different picture emerged for mean roughness, which tended to correlate negatively with pleasantness, but the effect becomes clearer in the *SD* of roughness. Although roughness *SD* decreased from low to wide to high position, the correlation between roughness and pleasantness is visible in all three positional subsets (coded by color) and is then not simply due to the main effect of position. For

TABLE I. Correlations between personal factors and an effect of distortion on perceived pleasantness, separately for asymmetric and symmetric distortion (Spearman; df = 82; Bonferroni corrected).

	Familiarity	GoldMSI	Electro	Classical	Metal	Rock
Asymmetric	$rho = -0.177$ $p > 0.10$	$rho = 0.258$ $p > 0.10$	$rho = -0.374$* $p < 0.001$	$rho = 0.353$* $p < 0.01$	$rho = 0.096$ $p > 0.10$	$rho = 0.095$ $p > 0.10$
Symmetric	$rho = -0.208$ $p > 0.10$	$rho = 0.150$ $p > 0.10$	$rho = -0.306$* $p < 0.05$	$rho = 0.238$ $p > 0.10$	$rho = 0.102$ $p > 0.10$	$rho = 0.085$ $p > 0.10$

type of distortion, the subgroup of asymmetrically distorted stimuli (in blue) showed high roughness *SD* and low pleasantness, and the subgroup of undistorted stimuli (in green) were of low roughness *SD* and high pleasantness. These two subgroups are driving the overall correlation between roughness *SD* and pleasantness. That is, part of the correlation between roughness *SD* and pleasantness was based on the applied distortion. Table III supports this notion, showing increased roughness mean and *SD* with increased distortion.

The negative correlation of mean spectral centroid and pleasantness was expected, as it matches the effect of position. However, Fig. 7 shows that negative trends were roughly present in all positions and all types of distortion, although some part of the correlation might be driven by the extremes (stimuli with very high spectral centroid in high position or asymmetrically distorted, and stimuli with low spectral centroid in low position or undistorted). For spectral flux and inharmonicity, there were no correlations with pleasantness.

IV. DISCUSSION

We investigated the perceived pleasantness of distorted and undistorted synthesizer stimuli, using triads in major or minor tonality and in low, high, or wide position. We programmed a specific audio-plugin to systematically manipulate asymmetric and symmetric distortion and to make the manipulation mathematically describable and replicable. To our knowledge, this is, therefore, the first study with this systematic approach to investigate pleasantness of distortion.

Our first interesting result is that in absolute terms, some of the distorted triads were evaluated as pleasant, namely, symmetric distortion of major triads in low and wide position. To our knowledge, we are the first to show statistically in an experimental study with isolated triads that, indeed, distorted sounds can be perceived as pleasant in absolute terms [see also Herbst (2019), Fig. 2, depicting a positive evaluation of the power and major chord in overdrive without reporting statistics]. We think this finding is important. It shows that even without any musical context, distorted sounds can be enjoyable and are not *ipso facto* aversive (e.g., McDermott, 2012).

TABLE II. Correlations between pleasantness evaluations and stimuli features. *p* values are not Bonferroni corrected. *, significance after Bonferroni correction with an adjusted α level of 0.006.

		rho ($n = 36$)	*p*
Amplitude envelope	*M*	0.528	<0.001*
	SD	0.426	0.010
Roughness (rms norm.)[a]	*M*	−0.421	0.011
	SD	−0.634	<0.001*
Spectral centroid	*M*	−0.596	<0.001*
	SD	0.241	0.157
Spectral flux	*M*	−0.211	0.216
	SD	0.204	0.232
Inharmonicity		0.000	0.998

[a] Root mean square normalized (rms norm.).

However, in relative terms, distorted stimuli were perceived as less pleasant than undistorted stimuli in our study. This is in line with Herbst (2019). As a new extension of the literature on distortion, we implemented a manipulation of position, which has been shown to affect consonance evaluations of triads in one study on undistorted stimuli (Lahdelma and Eerola, 2016). In addition, tonality effects (Arthurs *et al.*, 2018; Johnson-Laird *et al.*, 2012; Lahdelma and Eerola, 2016) have been demonstrated for undistorted triads. Our straightforward approach took these baseline differences into account by using difference scores. We found a stronger decrease in pleasantness by distortion for minor than major tonalities. That is, the effect of tonality lies above what can be expected from baseline differences. In addition, there was a stronger decrease for asymmetrically distorted triads than symmetrically. We manipulated distortion based on the mathematical foundations of polynomials, following a univocal, systematic account of distortion, with two types of distortion differing in spectral structure. Symmetric distortion produces only odd-numbered harmonics, which are less closely neighboring than the integer-valued harmonics that asymmetric distortion produces. By that, asymmetric distortion yields more roughness or interference of partials and should induce less perceived pleasantness accordingly. The latter was exactly what we found.

Somewhat surprising was the missing main effect of position for the difference score. The interference of partials is crucially related to the fundamental frequency of the complex tones and to ratings of consonance (Harrison and Pearce, 2020). Therefore, we expected an interaction between distortion and position and a systematic effect of position on the decrease in pleasantness at least between the low and high position, for which the intervals were kept the same but the fundamental frequency was not. However, there was no difference between low and high position. One potential reason for this result might be that the undistorted triads in high positions were not perceived as pleasant in absolute terms. Distortion type and tonality were eventually less effective on perceived pleasantness when the (undistorted, baseline) stimuli were not rated as pleasant in the first place. In addition, a limitation of our study is the range of implemented registers. It might very well be that using stimuli that span across the entire pitch register would have shown systematic effects. For example, using undistorted sounds, it has been demonstrated that consonance ratings follow an inverted u-shape function across the range of registers R1–R7 (Eerola and Lahdelma, 2022). In that study, consonance ratings for registers R4 and R5 were highly similar and on the peak of the function, which would predict no difference in pleasantness for our "low" (C4) and "high" position (C5). However, we found a clear difference in pleasantness ratings for undistorted triads. Nevertheless, for showing an interaction with the distortion effect, the more promising comparison might have been between positions with stronger differences in perceived consonance, e.g., very low (R1) and mid registers (R4).

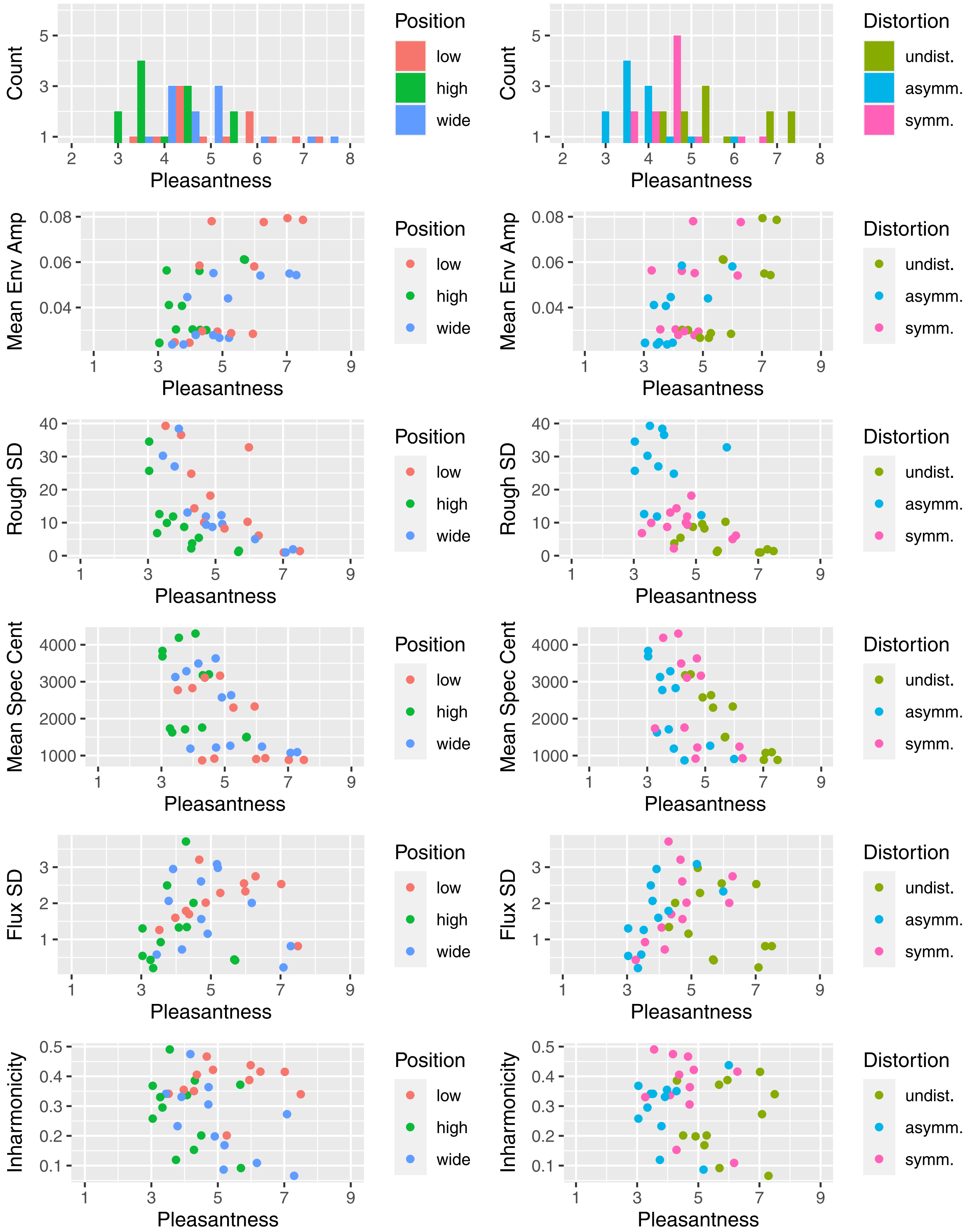

FIG. 7. Relations between stimulus-based mean perceived pleasantness and acoustic features for different positions and distortion types (for distributions of raw ratings, see supplemental Fig. S2)[2].

We then asked for individual differences in the effect of distortion, but self-rated familiarity with distorted music and music sophistication did not play a role. Results on music preference were mixed but explicable. Whereas preference for metal or rock did not relate to the effect of distortion on pleasantness, preference for electronic music did: The higher the preference for electronic music, the smaller the decrease in pleasantness by distortion. The stimuli applied in our study were synthesizer sounds. One other study showed a positive correlation of valence ratings for distorted sounds with the music preference of rock (Herbst, 2019), but that study applied guitar timbres. Thus, maybe applying genre-specific timbre is crucial to uncovering the relation between the evaluation of distortion and genre-specific

TABLE III. Acoustic properties of the stimuli split by distortion.

		Undistorted		Symmetric		Asymmetric	
		M	*SD*	*M*	*SD*	*M*	*SD*
Amplitude envelope	*M*	0.05	0.02	0.05	0.02	0.04	0.01
	SD	0.002	0.001	0.002	0.001	0.002	0.001
Roughness (rms norm.)	*M*	113.43	65.71	163.51	84.49	210.00	112.39
	SD	4.50	3.73	9.63	4.37	27.18	10.15
Spectral centroid	*M*	1928.97	870.64	2474.41	1295.72	2258.72	1108.17
	SD	74.61	33.09	56.52	18.75	67.85	14.95
Spectral flux	*M*	5.28	3.10	9.24	3.08	10.82	3.31
	SD	1.46	0.96	1.91	1.01	1.68	0.95
Inharmonicity		0.05	0.02	0.05	0.02	0.04	0.01

preferences. Further studies need to follow up on this issue by appropriate experimental manipulations.

Finally, we related the stimulus-based evaluations of pleasantness with the acoustic features of the stimuli, including undistorted and distorted stimuli. Higher levels of pleasantness were found for stimuli of higher mean intensity, lower roughness *SD*, and lower spectral centroid. The positive correlation on intensity was mildly affected by the position of the triads, depicted in Fig. 7. For roughness *SD*, the negative correlation seemed not to be confounded with position and might, therefore, be the best predictor of perceived pleasantness. Stimuli of different distortion types seem to group on the variable roughness *SD*, as can be expected, given the way the system SAUND manipulated distortion in this systematic and controlled way. Our results only partially match what can be expected given the literature (Herbst, 2019; Rice, 2020). The negative correlation of pleasantness with mean spectral centroid (sharpness) was reported before (Herbst, 2019); the correlation with roughness *SD* was not, but this is in agreement with the already reported correlation with roughness mean (Herbst, 2019). In contrast, we found a positive relation between sound intensity and pleasantness, whereas the earlier study reported a negative correlation (Herbst, 2019). These differences between studies might be partially due to the applied loudness levels and intensities. We had adjusted the stimuli on perceived loudness levels, which resulted in slight but measurable differences in sound intensities. This was a very different treatment from that in Herbst (2019). Also, we did not find a negative correlation of spectral flux mean or *SD* and mean roughness as in Herbst (2019). The latter was shown as a tendency in our data, which was not significant after Bonferroni correction. The first two were clearly absent. However, we were very careful in extracting the acoustic features. For example, we deleted the fade-in and fade-out sections before analyzing the acoustic features, as those would have created artifacts. We noted that our spectral flux measure was particularly vulnerable for the artifacts and would have resulted in a significant correlation with perceived pleasantness for measures including fade-in and fade-out sections. In general, multiple testing in such exploratory and complex designs is sensitive for α errors. Replications are therefore strongly needed in this research field.

For musicians and composers, it is interesting to note that the numerical effect of the distortion manipulation is stronger than those on tonality or position. That is, for music, effects of distortion will not disappear by music-inherent decisions such as changing tonality or position. Particularly for position, effects remain rather stable. Results are in line with other studies in other settings. For example, on a neural level, there are stronger effects (i.e., larger and earlier event-related responses) for sudden changes in distortedness than in harmonic structure (i.e., changes between the power chord and major triad; Virtala *et al.*, 2018).

We investigated the effect of distortion on self-reported pleasantness using isolated triads. Although we demonstrated that some distorted triads were perceived as pleasant in absolute terms, in relative terms, distorted triads were overall perceived as less pleasant than undistorted triads. These results are in line with research showing negative consequences of distortion, e.g., roughness and distortion make sounds annoying (McDermott, 2012); a rough in comparison to a simple harmonic sound speeds up an aversive, behavioral reaction (Taffou *et al.*, 2021); distortion has been added to loud stimuli to create aversive stimuli (Neumann and Waters, 2006; Heponiemi *et al.*, 2003); in other auditory domains like speech perception, a clean signal is beneficial, and distortion impacts speech intelligibility in an undesirable way (Kates and Arehart, 2005). These kinds of research imply that distortion might be generally undesirable. However, such an interpretation is clearly overstating. Distortion is at the core of the aesthetics of modern music production: "The closest thing to pure electric guitar tone—free of audible distortion—is a lifeless, one-dimensional sound (···). Yet when properly amplified (···), it becomes the most varied, versatile and character-laden instrument imaginable" (Poss, 1998, p. 45). Accordingly, music production practices have employed distortion strategically to enrich timbral features in a highly sophisticated manner for decades (Barbour, 1998). In contrast, in our design, responses were made within the context of listening to isolated triads. That is, the evaluation included a comparative judgment between isolated stimuli. Our interpretation cannot easily be transferred to complex music. Rather, our study stripped off the musical context and investigated distortion in an isolated context to understand basic differences in perceived pleasantness between the types of distorted stimuli, its position and tonality.

V. CONCLUSIONS

Distortion is sometimes regarded as undesirable noise or disturbance, despite its manifold usage in modern music production to enrich the variety of timbres. We extended prior research on perceived pleasantness of distorted guitar sounds (Herbst, 2019) by using synthetic timbres, comparing symmetric and asymmetric distortion, and including position and tonality as orthogonal factors. We applied a sophisticated design defining the effect of distortion as a difference score between evaluations of undistorted and distorted stimuli. Pleasantness decreased when triads were distorted, and the decrease was stronger for the minor than the major tonality, replicating what has been shown (Herbst, 2019). Position had only a minor effect on the decrease by distortion. This result was astonishing, as roughness and harmonicity are assumed to contribute to consonance, and these acoustic measures change for intervals presented in different registers (Harrison and Pearce, 2020). Indeed, in our data we found effects of roughness *SD* and mean spectral centroid (sharpness) on ratings of pleasantness. Different from other studies, sound intensity increased perceived pleasantness, and spectral flux as well as mean roughness had no effect. Position was not or was only marginally confounded with roughness *SD* and spectral centroid (sharpness), which might contribute to the missing overall positional effect. Also, enthusiasts of electronic music were less affected by distortion and not those of rock music. The diverging results are likely based on the stimulus material, including the manipulation of distortion. To uncover further stimulus-specific or listener-specific dependencies, more studies are desirable.

Importantly, we presented a tool to systematically manipulate polynomial distortion and invite researchers to use this open-source tool in further studies (Chemnitz, 2022). Applying this tool, we demonstrated that asymmetric distortion reduces pleasantness more than symmetric distortion. Finally, we showed that symmetrically distorted major triads were rated as pleasant on an absolute level, speaking against the prejudice that distortion is generally regarded as unpleasant.

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[1] There are a few methodological issues in Herbst (2019) that we think need to be optimized before firm conclusions can be drawn. For example, the degrees of freedom (df) in the analyses of variance (ANOVAs) do not match the number of participants but rather the recorded observation; the df in the stimulus-based correlations match the number of participants; also, each stimulus was evaluated once per subject, and ANOVAs were not based on means but single trial measures; data collection was in group settings, that is, stimuli were not randomized between participants but presented in a fixed serial order prone to serial order effects.

[2] See supplementary material at https://doi/org/10.1121/10.0020667 for additional analyses and figures.

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