“Do You Want to Hear a Magic Trick?”: Vocal Pitch Range Effects of Dutch on the Tritone Paradox

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Abstract

The tritone paradox is a compelling auditory illusion discovered by Diana Deutsch in 1986. Upon hearing a tritone interval (i.e. a tone pair related by half an octave) such as A#-D, any one listener might hear it ascend, whilst another listener might hear the same interval descend. The illusion is based on Shepard tones (1964), which are simple to identify in terms of pitch class, but complex in terms of specific relative tonal height. This makes it difficult for two of such tones spaced at an equal distance to determine which tone is higher than the other. However, much remains unknown about the different interpersonal factors that contribute to the mental strategies that lead to deciphering the complex intervals as either ascending or descending.

Previous research suggests that not someone's musicality, but the language variation spoken and heard during childhood might influence their perception of the tritone paradox. More specifically, it is thought that experience pertaining to the pitch range of a language would shape our general interpretation of which pitch classes are heard as higher or lower than others, in turn affecting our perception of the tritone illusion (Deutsch, 1987, 1990, 1994, 2004, 2007; Deutsch et al, 1991). In an attempt to unravel this psychoacoustic mystery further, this study examines the relationship between musical, spoken, and perceptive behaviour of people who had grown up in the Netherlands speaking Dutch as their first language.

Therefore, a group of 29 native Dutch participants were recruited for an online experiment. After completing a short background survey, the participants received a perception task in which they needed to identify tritone paradox intervals as either 'falling' or 'rising', and they were asked to record themselves reading aloud a passage of text, from which F0 measurements were drawn. Additionally, participants were presented with a tailored version of the Musical Ear Test (Correia et al., 2021, adapted from Wallentin et al., 2010), a standardised test to index their level of musicality. Based on the findings from these tasks, it was concluded that a) Dutch listeners of the tritone paradox follow a perception pattern similar to Californian American listeners (their mental orientations of the pitch class circle, reflecting which pitches they generally perceive as relatively higher than others, are both centred around peak pitch classes C-C#); b) level of musicality is not a key factor in someone's perception of the tritone paradox; and c) (Dutch) pitch range in speech does not correlate with perception of the tritone paradox. Nevertheless, since the (confirmed) hypothesis that Dutch and Californian listeners react similarly to the illusion was based solely on pitch range literature, it is expected that future replication of the study with a larger and more balanced participant population, and an improved methodology pertaining to spoken data collection could find more conclusive support for the theory that spoken pitch range influences tonal perception. Doing so would further contribute to gaining insight in the psychological connections between our spoken language and how we personally experience the auditory world around us.

Keywords: tritone paradox, auditory illusion, pitch range, Dutch, English, musicality, language-music connection, pitch perception.

"Do You Want to Hear a Magic Trick?": Vocal Pitch Range Effects of Dutch on the Tritone Paradox

It is almost like magic, how illusions can trick the brain into believing its own created version of reality. However, not everyone's brain might use the same strategies as others' in making sense out of ambiguous information. An example of an illusion that invokes such a psychologically diverse reaction is the tritone paradox. This auditory illusion, created by Diana Deutsch in 1986, has caused listeners to disagree on whether they hear the very same tritone interval (i.e. two sequential tones, spaced half an octave apart) as descending or ascending. The illusion rests on the principle of Shepard tones (1964), which are multiple tones, like on a key from a piano, that are stacked over multiple octaves, such as C2, C3, C4, etc. The amplitude, or the 'loudness', of each tone is adjusted so that the central tone is the loudest and the lower and higher sounds are quieter. Because of these features, the Shepard tones are easy to identify in terms of pitch class (C, D, F#, etc.), but not in specific relative height. When presented with such a Shepard tone pair that is related by half an octave, and thus spaced by an equal distance in semitones, it is difficult to determine based on relative distance which of the tones is higher than the other. However, although this explains the basis of the mysterious illusion, it does not explain exactly what personal factors can be attributed to why two listeners of a physically identical sound may genuinely perceive it in two vastly different ways.

Upon further research, Deutsch (1990, 1994) found that our linguistic background might play a key role in our auditory perception, when discovering that most listeners from California heard the tritone intervals in the opposite direction from listeners from the south of England. She ascribed the pitch range (i.e. how high and low our voices are during speech) of the language variation heard and spoken around us in our childhood to our perception pattern of the tritone paradox. To test this theory and as a contribution to the broader research shedding a light on the (linguistic) effects on our musical perception, this study focussed on native speakers of Dutch from the Netherlands (N=29). By doing so, this study aimed to explore the relationship between Dutch pitch range and the perception of the tritone paradox. In addition to this, musicality was included as a potential factor of influence to verify previous suggestions that musical ability was not an influential factor. With these goals in mind, this study sought to answer the questions as to how the Dutch population would perceive the tritone paradox (as compared to Californian American and Southern British English listeners), and the extent to which musicality, language, and specifically the Dutch pitch range would influence someone's perception of the tritone paradox.

To investigate these questions, an online experiment was launched, collecting participant's musicality index via an adapted version of the standardised Musical Ear Test (MET; Correia et al., 2021, adapted for Gorilla.sc from Wallentin et al., 2010) their perceptions of the tritone paradox and their pitch range via a self-recorded audio fragment of them reading aloud a passage of text[1]. These data would serve to test the proposed hypotheses that Dutch speakers would exhibit a distinct perception pattern which would be more in line with the Californian pattern than the Southern British English pattern as found earlier by Deutsch (1994), that musicality would not play a role in someone's perception of the tritone paradox, but that someone's (Dutch) pitch range in speech would influence the way in which they would hear the auditory illusion. Exploring these hypotheses helps us gain a deeper understanding of the complexity of the human brain and of the influence of spoken language on our individual musical experiences.

[1] Initially, the participant recruitment aimed at both native speakers of Southern British English and of Dutch to compare these linguistic groups, but due to technical complications and a limited reach, only Dutch data was suitable for analysis.

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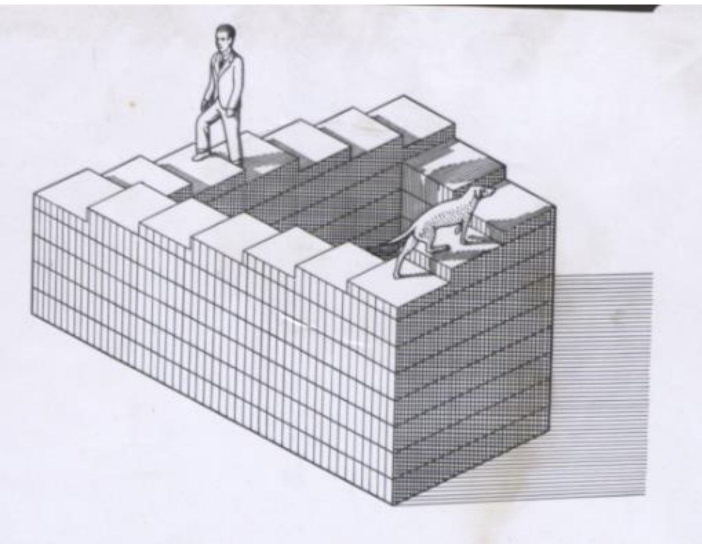
Background

Illusions

Illusions are a well-known psychological phenomenon that trick our brain into misperceiving information from a sensory ambiguous source (Warren & Warren, 1970). Upon hearing the word 'illusions', we might directly imagine various optical illusions. These images deceive the viewer into believing they are seeing, for instance, physically impossible perspectives ('Penrose Stairs', Figure 1), movement in a motionless image ('The Autumn Color Swamp', Figure 2), or two different depictions in one image ('My Wife and My Mother-in-Law', Figure 3).

Figure 1

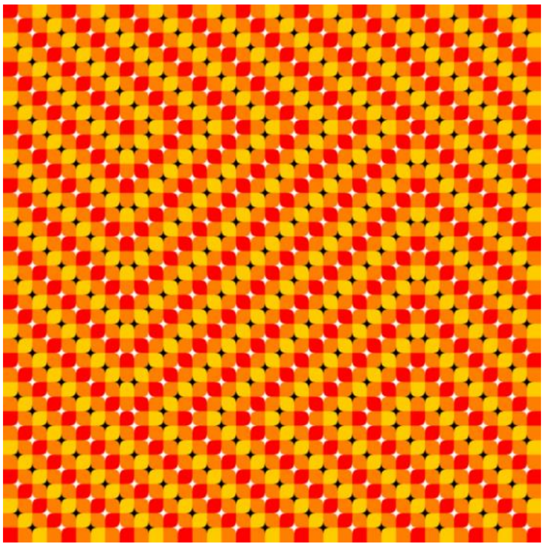
The Penrose Stairs Illusion.



Note. Adapted from L.S. Penrose. (1958). The Penrose Stairs. [digital]. Wellcome Collection, London, UK. Retrieved from https://wellcomecollection.org/works/gtyrttpz.

Figure 2

The Autumn Color Swamp.



Note. Adapted from: Kitaoka, A. (2002). The Autumn Colour Swamp [Digital]. Retrieved from https://www.psy.ritsumei.ac.jp/akitaoka/ACswampe.html

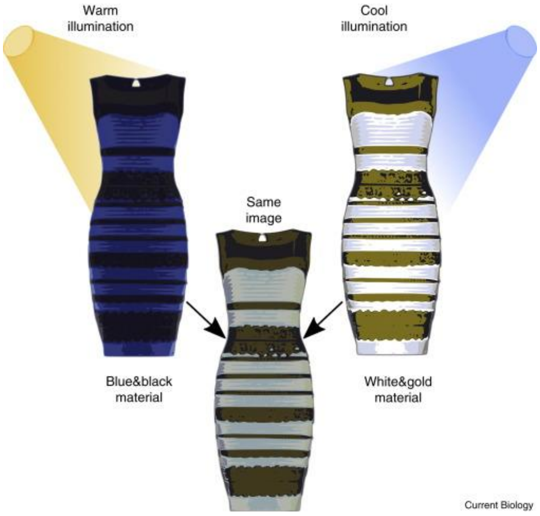
Figure 3

'My Wife and My Mother-in-Law*. They Are Both in This Picture – Find Them'.*

Note. Adapted from: William, H. A. (1915). My Wife and My Mother-in-Law [Print]. In Puck, p. 11. Retrieved from https://www.loc.gov/resource/cph.3b45252/.

Figure 4

The Colour Constancy Explanation for #thedress



Note: Adapted from: Brainard, D.H., Hurlbert, A.C (2015). Colour vision: understanding #TheDress. *Current Biology*, 25, R551-R554. https://doi.org/10.1016/j.cub.2015.05.020

A more contemporary example of an optical illusion that has been circulating the internet since February 2015 is known as 'The Dress'. This photograph of a dual toned striped dress sparked global digital debate via social media on whether the attire would be black-and-blue coloured or yellow-and-gold. Through this viral image and the subsequent dispute, the general public was reminded or even made aware that the perception of colour is not universally identical for everyone. As Brainard and Hulbert (2015) explain, this is partially due to the interpersonal differences of correction for colour illumination. As Figure 4 illustrates, this entails that when an object's intrinsic colour is altered by the warmth of the light reflected onto the object and into the eye, we correct for that inconsistent factor of illumination, which is why we can often perceive a red apple as a 'red' apple in both warm and cool light. Brainard and Hulbert further surmised that people's brains subconsciously rely on different cues in the context of an image to correct for cool or warm reflective light. In the case of The Dress, these different colour correcting strategies do not align for everyone, leading to the different opinions on the intrinsic colours of the dress in the image. Illusions such as these reveal how we might question the certainty of intrinsicality when we suddenly realise that people have vastly different perceptions of a seemingly identical sensory input, such as an image or a colour.

Auditory Illusions: The Tritone Paradox

Much like the optical illusion of The Dress caused dispute on sensory perception, the sound-based illusion of the 'tritone paradox' has the same effect on people. This is a type of auditory illusion, which arises 'when the mind synthesises missing information based on what they expect to hear' (Warren & Warren, 1970). In this case, the compensation for missing information happens differently amongst listeners, resulting in different perceptions of the same stimulus. Namely, upon hearing two half-octave related tones, listeners disagree amongst each other whether they hear the tones ascend or descend. This auditory illusion was initially described by Prof. Diana Deutsch in 1986 and revolves around the auditory perception of complex musical pitch.

Pitch (tonal height) can be expressed linearly by acoustic frequency in Hertz (Hz) values or classified logarithmically by musical pitch or semitones as represented by the musical scale. This musical notation rests on the principle of 'pitch classes' that are experienced as similar sounding across various heights, due to this logarithmic nature. For example, within the pitch class 'A', we find A3 located at 220 Hz, A4 at 440 Hz and A5 at 880 Hz. Each time this Hertz value is doubled, the semitone rises an octave (as represented by the number behind the pitch class letter). One octave within the western musical scale is generally accepted to include 12 semitones (A, A#, B, C, C#, D, D#, E, F, F#, G, G#). Two tones related by half an octave is referred to as a 'tritone'[2], such as 'A-D#', 'C-F#' or their respective reversals. The 'tritone paradox' includes artificially manipulated tritone intervals as such[3].

The main artificial manipulation responsible for the tritone illusion is the super-positioning of one pitch class over six octaves, combining for example A2, A3, A4, A5, A6, and A7. Stacking a sinusoid (a simple, perfect wave form) to hear multiple octaves simultaneously in such a manner is referred to as a 'Shepard tone', a phenomenon created by Richard Shepard in 1964. This is the root of what causes listeners of the tritone illusion to disagree amongst each other on their perceived direction of the tones (falling or rising). Namely, these Shepard tones can easily be defined by their pitch

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[2] The term 'tritone' is derived from the three full tone steps (or six semitone steps) that separate two tritones.
[3] For an auditory example of the tonal intervals as used in the tritone paradox, please listen to these four examples from Deutsch's compact disc 'Musical Illusions and Paradoxes' (1995).

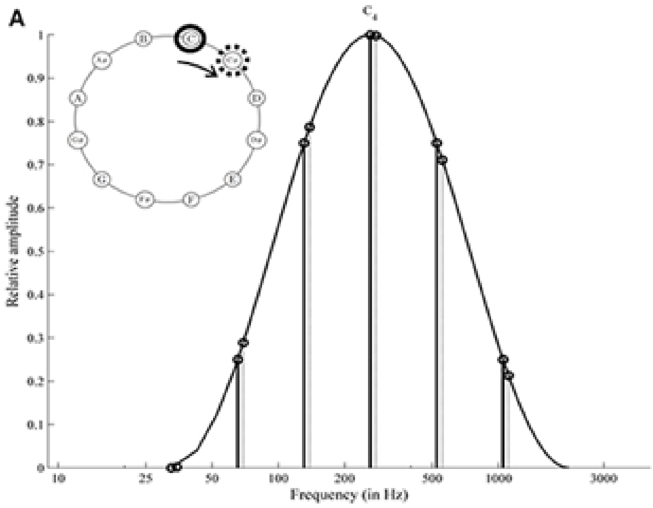
classes, but not in terms of relative height or specific pitch. In other words, it is relatively simple to recognise whether an octave-complex tone is an A or an D# in musical terms, but not what the precise height of the A and D# would be in relation to each other, since an A4 is lower than a D#4, but a D#4 is in turn lower than an A5, for example. This ambiguity in tonal height is what makes the tritone paradox an auditory illusion, since we cannot reliably identify exactly what information we are being presented with when listening to the intervals. Shepard originally stacked eight octaves simultaneously, but the design of Deutsch's 1987 Tritone Paradox stimuli consists of six octave-related sinusoids. Since each tone pair included in the tritone paradox is spaced evenly and it is difficult to hear which one is higher or lower, people tend to disagree on the actual relative direction when hearing such an interval.

Additionally, spectral filters are applied to the Shepard tones to make it harder for the listener to recognise that they are actually listening to multiple octaves per tone fragment (Deutsch, 1986; Malek 2018). These fixed logarithmic envelopes assign the highest relative amplitude (loudness) to the central frequency, gradually fading out the higher and lower pitches. This place auditory prominence on the central frequency, making it less obvious to the brain that multiple frequencies are being played simultaneously. This explains the bell-shaped curve visualisation of the filter, as can be seen in the example in Figure 5. The image illustrates that one pitch is amplified most within a tonal pair. As a result, the listener's auditory attention is gravitated towards a central frequency, making it difficult to determine relative tonal height between two tritones (Deutsch, 1986; 1991; 1994; Malek, 2018; Shepard, 1964).

Listening to a scale sequence manipulated as Shepard tones creates the illusion of a never ending ascending or descending pattern, dependent on the direction of playback. This phenomenon is otherwise known as the Shepard Scale (1964). It is often compared to a musical barber's pole or the earlier mentioned Penrose staircase illusion, due to its seemingly everlasting circularity. Jean-Claude Risset (1968) famously adapted the Shepard scale into the smoother 'Risset Glide', that is often related to the auditory sensation of falling into a bottomless pit (Deutsch, 1986, p. 66). Illusions such as these illustrate well how the musical scale can not only be perceived linearly, as can be envisioned as the keys laid out on a piano, but also circularly due to the pitch classes. Additionally, considering the dimension of height expressed through the octaves, the chromatic scale could be imagined as a helix moving up or down, with each pitch class aligned in a vertical line, as in Figure 6.

Figure 5

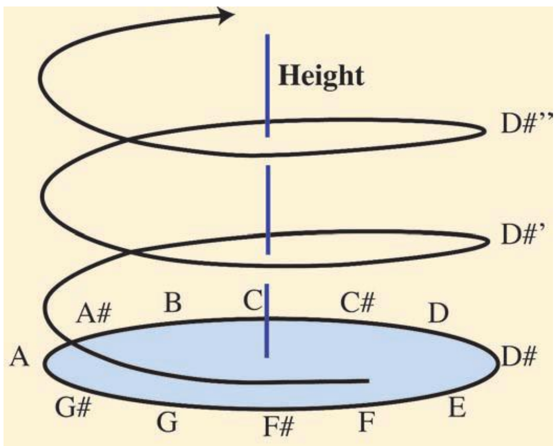
Spectral structure of Shepard tones: C and C# are generated under an envelope centred at C4 (261.63 Hz).



Note. Adapted from “Pitch Class and Envelope Effects in the tritone paradox Are Mediated by Differently Pronounced Frequency Preference Regions.” by S. Malek, 2018, *Frontiers in Psychology, 9*. https://doi.org/10.3389/fpsyg.2018.01590

Figure 6

The Helical Model of Pitch.



Note. Adapted from “The Paradox of Pitch Circularity” by D. Deutsch, 2010, in *Acoustics Today*, *6*(3), 8-14. https://doi.org.10.1121/1.3488670.

Technical and Musical Correlates of the Tritone Paradox

Now, since the tritone illusion, unlike The Dress illusion from 2015, has actually been artificially constructed for the purpose of being an illusion, we are already aware of the technical properties that cause the ambiguity that leads to people disagreeing on what they hear in the tritone paradox. However, this does not explain yet why one person hears an interval as ascending and someone else will hear that identical interval as descending. In her extensive research on the tritone paradox, Deutsch has been exploring various potential factors that would influence personal preference for perceiving a certain tonal direction. For instance, she has found that playing a tonal pattern in one key can be heard as ascending whilst in another key, the same pattern is suddenly heard as descending (1986). Moreover, the playback speed also manipulated people's judgements: 'if the tape is first played at normal speed, and is then sped up so that the tones are transposed up a half octave, listeners who first heard the pattern as ascending will now hear it as descending, and listeners who first heard the pattern as descending will now hear it as ascending!' (Deutsch, 1986, p. 5). Nonetheless, although personal judgement could be manipulated via these factors, dissimilar perception patterns between participants remained; they did not break the illusion.

Furthermore, no correlates were found with playback amplitude level differences, stereo differences, or the participant's level of musicality (Deutsch et al., 1987). The latter is interesting, as it might be intuitive to expect highly musically trained listeners to perform better at a musical pitch perception task than participants that are less musically skilled. Indeed with this estimation, in her first experiments with the tritone paradox, Deutsch (1986, 1987) consulted musically schooled participants to identify the tonal directions of the ambiguous intervals, since surely these would prove best whether the illusion worked properly. However, even the musically trained listeners disagreed amongst each other in these tests and Deutsch and Kuyper (1987) later found that the effect of the tritone paradox was not limited by a selected group of specialised listeners.

Although these multiple literatures aptly suggest that musical training is not a factor of influence for someone's perception of the tritone paradox, these papers are not quite up-to-date anymore and only consider academical musical training in the classification of someone's musicality. A modern standardised test such as the Musical Ear Test (MET; Wallentin et al., 2010) offers more specific insight on a participant's practical musical perception skills. The MET can be used to reliably distinguish professional, amateur, and non-musicians and, specific degrees of musicality (in this context: the ability to recognise melodies and rhythms) amongst different types of musicians (e.g. rhythmic, jazz/rock, classical, technical, etc) and non-musicians. This musical perception test is divided into two similarly structured sections of each 52 randomised trials: one which tests melody (with piano sounds) and one that tests rhythmic recognition (with wood block sounds). The rhythmic dimension might not be as relevant to the study of the tritone paradox as the melodic dimension, since the illusion is focussed on pitch discrimination. Nevertheless, a test such as the MET could aid the verification of earlier found results that imply that degree of musicality does not have an effect on the tritone paradox. At this moment, there still has been no such combination of tests presented.

When looking at the currently limited and dated literature on the tritone paradox, we are left to wonder what interpersonal factors play a role in the different perception patterns of the auditory illusion. This current study aims to contribute to the academic body of literature that deciphers this psychoacoustic mystery.

Language and the Tritone Paradox

Specifically, this research explores the influence of language background on the perceptions of the tritone paradox. Although unlikely for a non-verbal illusion at first glance, language has been recognised as a key motivator for someone's judgement of these complex tones (Deutsch, 1991, 1994; Deutsch et al., 1990, 2004). The idea that language might be an influential factor came to Deutsch when she realised she – having grown up in the south of England – and her visitors from London heard the tritone paradox similarly amongst each other, but differently from her Californian students (Deutsch**,** 2019, p. 75). Additionally, Deutsch found that the various hearing patterns gathered in her 1997 study on the tritone paradox pointed towards different orientations of the pitch class circle by the participants, in terms of pitch height. These orientations are represented by the two pitches that would stand at the top of the circle ('peak pitches'), indicating which pitch classes are subconsciously considered 'higher' and which 'lower' by a person. From these two findings, Deutsch surmised that 1) every person has a mental representation of the pitch class circle; 2) the orientation of this circle is formed by the speech patterns someone has been exposed to frequently in their life, especially in childhood; and that 3) these two points share a connection to how someone hears the tritone paradox (Deutsch, 2019). In other words, Deutsch expected that the language varieties we were most frequently exposed to during our childhood have not only influenced our own speech, but also our auditory perception of relative pitch height. This influence of language experience would manifest itself in the octave band of a person's speech 'containing the largest number of pitch values for their spoken speech', which in turn would be relatable to someone's personal interpretation of the tritone paradox (Deutsch et al., 2004).

To test her hypothesis, Deutsch proceeded to explore linguistic influence on people's perception of the tritone paradox. By comparing the perception patterns of English speakers from California and South England (1991), she found that these speakers of the same language but different regiolects heard the tritone paradox strikingly differently from each other. Namely, Californian American (CA) subjects were more likely to perceive pitch classes between B and D# as relatively high, whereas pitch classes between F# and G# were perceived as higher by the Southern British English (SBE) participants. In the context of the tritone paradox, this meant that someone who follows an SBE perception pattern hears the interval F#-C as falling, whereas someone with a CA pattern would hear the same tone pair as rising.

According to Deutsch, these peak pitch classes as derived from the participants' tritone paradox judgements would correlate with the higher end of the participants' pitch range in speech. This 'pitch range'[4] describes how relatively high or low a person's average speaking voice is and how far their minimum and maximum frequencies spread. In other words, if someone has a lower or higher voice, and if they speak in a monotone fashion or if their pitch fluctuates. Although direct comparisons between the pitch ranges of SBE and CA had not yet been made, Deutsch inferred from the literature available at that time that the CA pitch range would be lower than that of SBE (Deutsch, 1994; Hanley et al., 1966; Collier, 1991; Willems et al., 1988). She confirmed her expectation based on this previous point, that when the tritones would be generated under spectral envelope centred at a lower pitch (C4 and F#4), CA participants would show a stronger perception profile than SBE participants, who would

[4] In different literatures, the pitch range is also sometimes used synonymously to the 'F0 range' or the 'Speech Fundamental Frequency' (SFF; Yamazawa & Hollien, 1992).

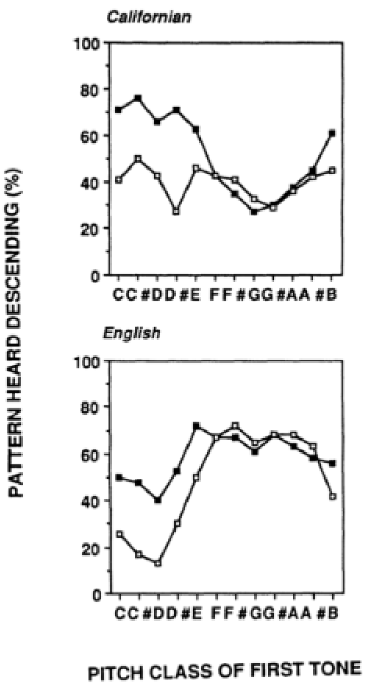
in turn react stronger to tritones generated under a higher centred spectral envelope (at C5 and F#5) than CA participants, as can be seen in Figure 7. In this graph from Deutsch's 1994 follow up study, the dark coloured squares represent the judgements of the higher spectral envelope generated tritones, and the open squares represent those under lower spectral envelopes. It illustrated that the two perception patterns Deutsch had already found for CA and SBE participants in 1991 could be emphasised by manipulating the stimuli to reflect the relative heights of the language variety pitch ranges.

This idea that language variety might influence our perception of the illusion was further supported after examining participants from the same area but whose parents came from different regions. When testing participants born and raised in Youngstown Ohio, those whose parents also grew up in Youngstown perceived the illusion differently than those whose parents came from a different part of America (Deutsch, 1994). Additionally, Vietnamese immigrants who moved to California at early and at late stages in their lives (who either spoke English very well and were less proficient in Vietnamese or the other way around), heard the illusion strikingly similar to each other – but less so compared to the native Californian group from the 1994 study (Deutsch, 2004, 2007). This indicated a stronger influence from someone's first language (L1) than their second language (L2). This same study included a second experiment that measured pitch ranges (expressed as the two pitch classes delimiting the upper range of speech) from short passages of Vietnamese speech from six participants[5]. When comparing each participant's individual peak pitch classes from their speech with those from the tritone perception experiment, a strong correlation was found. In other words, the peak pitch classes in their L1 speech were similar to the pitch classes they perceived as 'highest' amongst the pitch class circle. Although the limited population size should not be overlooked, and no comparison was drawn between L1 Vietnamese and L1 Californian pitch range, this study's findings suggested that not just any language(s) spoken by a participant could be of influence on someone's perception of the tritone paradox, but more specifically the first language experience (obtained in early life).

[5] Deutsch (2004) did not specify whether these six Vietnamese participants moved to California early or later in their lives, but each of them were fluent in Vietnamese and nonfluent in English.

Figure 7

Percentages of Judgments that a Tone Pair Formed a Descending Pattern, Plotted as a Function of the Pitch Class of the First Tone of the Pair.



Note: adapted from Deutsch. D. 1994. 'The Tritone Paradox: Some Further Geographical Correlates' in *Music Perception,* 12:1, p. 131. The dark squares represent tones generated under the higher envelope; the white squares represent tones generated under the lower envelope.

Hence, Deutsch attributed our speech and hearing to our perception of the tritone paradox, expecting it might be related to typical pitch ranges. However, she admitted that proper research comparing specific pitch ranges of the languages and regiolects she had investigated was often lacking at the time (p. 130, 1994). Blom (2023) attempted contributing to this aim by looking at first language (L1) Dutch and L1 Southern British English speakers, and at Dutch second language (L2) English speakers with a Dutch, Southern British or American English accent. However, data on L1 typical pitch range was explored exclusively through literature review. Additionally, the tritone stimuli for that study were generated in a different fashion than Deutsch's, without the spectral envelopes for example, which expectedly lead to the illusion partially losing its paradoxicality in the experiment. This conclusion was drawn because the participants agreed upon the direction of the intervals more often than expected, both within a language and cross-linguistically. It is therefore of current academic interest to follow the original chain of custody more accurately for proper replication whilst also measuring and comparing pitch ranges of participants when investigating the linguistic influence of our perceptions of the tritone paradox.

Furthermore, although Deutsch is currently still by great extent the leading expert of the research field relating to the tritone paradox, she is not the only researcher who has studied the interaction between our language background and our musical experience. For example, in an incredibly large-scale study on musical abilities in a multitude of languages, Liu et al. (2023) investigated 19 tonal languages (N=34,034), 29 non-tonal languages (N= 442,198) and 6 pitch-accented languages- (N=16,868) from 203 countries. The study initiated with a meta-analysis and proceeded with an empirical section where participants received a melodic discrimination task (the MET), a mistuning perception task, and a beat alignment task. The results reflected that speakers of tonal languages were better at discriminating melodies than speakers of non-tonal languages, but the opposite was true for rhythm-based processing. This was in line with their expectations, since tonal languages rely on pitch (tonal height of the voice) to identify words and meaning in contrast to non-tonal languages that only use pitch for intonational purposes to convey emotion, emphasis and syntactic (sentence based) structures. Therefore, it did not come as a surprise that speakers of a heavily pitch-reliant language would also perform well in pitch-reliant melody tests. Amongst these findings, the level of previously acquired musical training did not influence these trends.

Interestingly, Choi (2021) investigated the pitch and rhythm perception of Cantonese and English musicians and nonmusicians (N=57) and found that non-musically trained participants had a performance advantage if they spoke the tone-language Cantonese, whereas this linguistic effect was not found amongst the musically trained participants. This indicated that the influence of language experience on musical perception accuracy was actually to some extent facilitated or limited by a person’s level of musicality. However, Liu et al. (2023) explicitly remark in their paper that tonal languages are often sampled narrowly in music-language interaction studies, resulting in an abundance of studies on Cantonese compared to American English, as is also the case in the Choi (2021) study. Lui et al. warn that such a narrow linguistic scope in literature might unjustifiably generalise the linguistic effects of other (tonal) languages.

Spoken Pitch Range and the Tritone Paradox

It is accepted that men's pitch ranges in speech are most often lower than women's, and that children produce higher pitches than adults (Yamazawa & Hollien, 1992). Additionally, it has been found that the greatest portion of an individual's F0 contour covers approximately an octave, regardless of their gender (Haan & van Heuven, 2012; Dolson, 1994). For that reason, pitch range could also be expressed in terms of an 'octave band' rather than Hertz values, as Deutsch (1991, 1994) did when comparing pitch range and tritone illusion perception patterns. In this regard, the upper limits of the octave band as expressed in pitch classes were used to represent someone's pitch range, rather than their specific Hertz values. Aside from being able to compare tritone perception patterns in this fashion, defining pitch range as pitch class (a semitone relation) allows for a logarithmic comparison of sound rather than a linear, which is more representable to how pitch difference is perceived by the human ear. For instance, although the distances in Hertz values between the semitones A1 (220 Hz) and A2 (440 Hz), and A2 and A3 (880 Hz) are 220 Hz and 440 Hz, respectively, humans perceive the distances between these pitches as of similar size (one octave each).

Furthermore, not only different genders tend to have differences in pitch ranges, but languages and language varieties seem to differ amongst each other too. These variations in spoken language have even been discovered to be reflected in sung and rapped music. For example, Gilbers et al. (2020) brought to light that the typical pitch ranges of the more fluctuant West Coast African-American English rappers and the more monotonous East Coast African-American English rappers were echoed significantly in the production of their melodic pitch contours found in their music. This implies that aside from simple independent preferences of musical style that could change from one musician to another, the music produced and heard by East Coast African-American English musicians as compared to those from the West Coast is defined by their distinct language variation-based pitch range conversational language. In other words, the tonal characteristics of the specific language we generally hear and speak influences our musical style in production. This current study aims to investigate the extent to which our language experience is involved with our perceptions of music.

With this goal in mind, an attempt was made to add Dutch to the present body of research on linguistic effects on the tritone paradox, comparing it to what is already known about Californian and Southern British English speech and perception patterns. In their 2003 book describing and comparing Dutch and RP English[6] phonetic characteristics, Collins & Mees explain that RP English has a wider pitch range and reaches lower frequencies in general, compared to Dutch. They continue to illustrate this by saying that ‘the English accusation that Dutch intonation sounds dull and monotonous is matched by the Dutch feeling that English patterns are ‘exaggerated’ and ‘affected’’ (p. 284). In a later chapter comparing RP English and General American English (GA), they make a similar comparison between the two varieties of English: ‘American English can strike a British ear as monotonous. British English intonation can sound 'exaggerated' or 'affected ' to Americans’ (p. 309). Although they do not explicitly mention general pitch range here, the quote implies that GA F0 range is narrower compared to the RP pitch range. Additionally, other studies add to this comparison by describing British English pitch range as relatively high and Californian English as relatively low (Deutsch, 1994; Hanley, et al., 1966; Willems, Collier & ‘t Hart, 1988).

It is important to note that the terms used in the 2003 study by Collins & Mees to represent these English and American variations of English are different to CA and SBE discussed by the body of works of Deutsch. Therefore, a comparison between these varieties might not be entirely righteous of the language varieties in question. However, until the current research gap pertaining to the cross-examination of F0 range from different languages is thoroughly improved upon with novel data, these instances of inference remain to base the present hypotheses off.

Nevertheless, based on the available research, Southern British or RP English are expected produce the lowest and widest pitch range out of these three discussed languages. In contrast, General and Californian American English, and Dutch seem higher and narrower in comparison to the British English variety, but it is uncertain how high or low the pitch ranges of American English and Dutch are compared to each other. In the context of the tritone paradox, it would imply that Dutch listeners

[6] A term often used interchangeably with SBE, referring to ‘Received Pronunciation’.

would be expected to react more similarly to the American pattern as found by Deutsch et al. (1991) than to the Southern British English pattern.

Research Questions and Hypotheses

Building on previously discussed established research about the tritone paradox and the influence of language background on our perception of the illusion, this presently proposed study aims to help narrow the current knowledge gap pertaining to the tritone paradox. This objective will be embodied by the investigation of the following research questions:

1. How do native Dutch listeners perceive the tritone paradox?
    a. How does this compare to what is known about Californian English and Southern British English listeners?
2. To what extent can someone's perception of the tritone paradox be attributed to their melodical musicality?
3. To what extent can someone's perception of the tritone paradox be attributed to their personal pitch range?
    a. To what extent can a native Dutch person's perception of the tritone paradox be attributed to typical L1 pitch range?

Drawing on the established literature gathered in the above section, it is hypothesised that:

1. Native Dutch listeners of the tritone paradox will perceive the illusion similarly amongst each other;
    a. Native Dutch listeners of the tritone paradox will perceive the illusion more similarly to Californian listeners than to SBE listeners, as gathered from the data in Deutsch et al. 1991;
2. Musicality will not play a large part in someone's perception of the tritone paradox;
3. Listeners of the tritone paradox with similar pitch ranges in speech will hear the illusion similarly amongst each other, but differently compared to listeners with other pitch ranges in speech;

b. A Dutch listener's perception pattern of the tritone paradox can be related to their typical L1 pitch range in speech.

Ultimately, by investigating the linguistic influence of this non-linguistic musical illusion, this proposed study aimed to contribute to the broader discourse concerning the language-music interaction by exploring how strongly the languages we hear and speak since our childhood can influence the way in which we perceive and experience complex tones.

Method

Participants

29 native Dutch participants were involved in this current experiment. The participant population consisted of 24 women, one non-binary person and four men, with a total age range of 20-68 years old (mean age = 32). One participant who had completed the experiment has been excluded from the afore mentioned data due to a self-reported complex hearing disability, including cookie bite syndrome (mid-range frequency hearing loss).

Originally, this experiment was also aimed at native speakers of SBE who grew up in the south of England. However, since this group only yielded eleven remote participants of whom eventually merely one was born and raised in the south of England (or the country all together), it was decided that this would not produce neither reliable nor representative results and should be dropped from the data. Thus, the subsequent data analysis from this experiment will be limited to the discussion of Dutch participants exclusively. Data pertaining to SBE speakers will be taken from the literature as provided in the background section.

Participants were recruited through social media (Facebook, Instagram, WhatsApp, LinkedIn), posters at the University of Leiden and the British Embassy in the Netherlands, and by word of mouth. Participation was voluntary and non-rewarded, and participants could stop or withdraw at any desired moment.

Experimental procedure

The experiment, including the background survey and the tasks, was conducted online on Gorilla Experiment Builder (Gorilla.sc, 2024). Participants were instructed to position themselves in a quiet environment and to use headphones rather than speakers. Additionally, after the questionnaire, participants were informed that the experiment itself would last an estimated 15 minutes and consisted of four parts: the headphone check, a standardised melody identification test, a perception task, and a production task.

Before participating in the anonymous questionnaire and subsequent tasks, the participant would be asked for their native language, in which they would continue the rest of the experiment. Then, in their native language, the participant was presented with a consent form they needed to read and accept to continue with the procedure. The online experiment then proceeded with a questionnaire, inquiring relevant personal background information from the participants, such as where they were born, what region they grew up in, potential hearing and speech impairments, etc. (see Appendix I for the full questionnaire). This questionnaire was followed by two standardised tests to gain further insight in the participants' auditory abilities.

The first of these tests included a headphone check test with six auditory distinction trials to ensure the use of headphones or earphones rather than speakers (Woods et al., 2017). This test consisted of six trials of each three low frequency stereo and mono tones with varying volumes. Each set, the participant was asked to report which of the three tones was the softest. Those who scored less than 4/6 on this test were automatically excluded for not proving reliably that they were using headphones.

The second standardised test was a shortened adaptation of the Musical Ear Test (MET). This test was adapted for the online experiment platform Gorilla (www.Gorilla.sc) by Correia et al. (2021) based on the original test created by Wallentin et al. (2010). The MET served to display a degree of participants' musical sophistication regarding melody recognition and a sense of tonal differentiation. For the purpose of this current thesis on the tritone paradox, the test was translated to Dutch by this researcher. The melody recognition test consisted of eleven trials, each including two melodic phrases. The participant was given a response time limit of five seconds within which they would need to report via buttons whether the two melodic phrases were identical or not. The test was preceded with two additional practice trials. Contrary to the previous test, the outcome of the MET was not used as an exclusion criterion but simply as an indexation of (a-)musicality to evaluate for a potential influence.

In earlier reports, (Deutsch, 1986, 1987) musicality or musical training was disregarded as a significant influential factor for a person's perception of the tritone paradox. In this current study, the MET monitored melodic (a-)musicality to verify Deutsch's disregard of musical skill as an influential factor for someone's perception of the auditory illusion. Each trial weighs equally, excluding the practice trials; a participant can score a maximum of eleven points at the end of the test. These were later categorised in 'Low', 'Medium' and 'High' scores.

For the perception task, participants received 72 tritone intervals, divided into three blocks. Each block of tone pairs included two groups of twelve intervals. Participants were asked to identify as rising ('omhoog') or falling ('omlaag') through two buttons on the screen. Stimuli used in this task were taken from Deutsch's (1995) CD and included six blocks of the same twelve tritone intervals (C-F#, F#-C, D#-A, A-D#, G-C#, C#-G, and each of their respective counter directions). The stimuli were randomly distributed per block. Each individual tone within a tone pair had a duration of approximately 500 milliseconds and there were no gaps separating the tones within an interval. Participants received a time limit of 5000 milliseconds to respond before continuing automatically to the next interval. In between the three blocks of stimuli, the participants were given a checkpoint screen allowing them to take a short break before continuing. This test was not preceded by a practice trial.

The last task of the experiment was a speech production task. The participant was given a short excerpt from Alice in Wonderland (Caroll, 1866/1948) in their L1 and were asked to record themselves reading it aloud. Free speech was not preferred for this task, because it could elicit unexpected speech variation. Additionally, considering the initial goal of collecting data from both Dutch and SBE participant, using a standardised text allowed for a certain inter-personal consistency and academic replicability. This specific text was chosen because the two language versions were similar in terms of phrasings, sentence length and content, allowing for an interlinguistic comparison.

Participants were offered a mandatory microphone test before partaking in the production task to ensure recording. The speech recordings were automatically saved in WEBM format when advancing to the last screen. The recordings were collected to measure the participants' individual pitch contours and to validate literature pertaining typical L1 Dutch pitch ranges (Collins & Mees, 2003; Deutsch, 1990, 1994; Willems et al., 1988).

Data Analysis Procedure

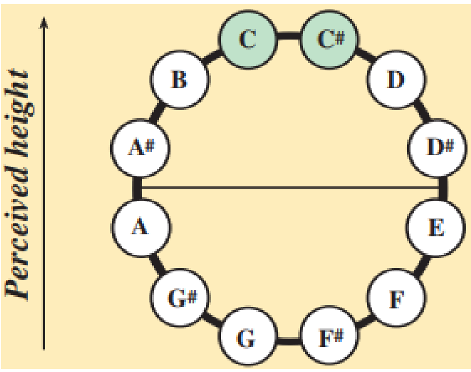
Tritone Perception Analysis

Mirroring Deutsch (1986), perceptions of the tritone paradox were expressed in peak pitches in someone's mental orientation of the pitch class circle. To obtain those, pitch class templates were created based on the method by Deutsch (1986). For each participant, it was collected how often they heard each tritone interval (which were repeated six times during the experiment) as descending more often than others. When an interval was heard as descending, it implies that the first tone of the pair would have been heard as higher than the subsequent tone within the tritone pair. For that reason, the intervals were expressed as their first tone of the sequence.

Subsequently, a personal pitch class circle was oriented. Such a circular representation of the 12-tone scale was divided in a 'lower half' and a 'higher half' of six pitch classes each, resulting in two pitch classes at the top of the circle. These two together were recognised as the 'peak pitch

Figure 8

Orientation of the Pitch Class Circle for a Participant, in which C and C# are Peak Pitch Classes.



Note: Adapted from Deutsch. D., A Musical Paradox (1986).

classes' and represent a person's perception pattern. To determine between which tones the bisection of the circle should take place, the largest difference between occurrences of descending tokens per half should have occurred. The largest difference is found when dividing the total descending scores for each oriented half of the circle results in the largest number. In other words, the top half of the circle should contain the six tones perceived as highest within their interval pairs most often, and the bottom half should contain the six pitches perceived the least frequently as 'higher'. Splitting the circle in half any other way would have resulted in a smaller difference between the total occurrence counts. The pitch class circle was then always oriented (or 'turned') in such a way that the two halves were split via a horizontal border, separating the twelve tones into two groups of six. An illustration of this from Deutsch (1986) can be seen in Figure 8. The two tones that were placed at the top of this pitch class circle determined the participant's two peak pitch classes, therefore representing their perception of the tritone paradox. This process was repeated for each participant. Finally, these perception patterns were collected to portray the overall perception pattern of Dutch.

F0 Analysis

To test if the tritone paradox perceptions are related to a person's typical L1 pitch range, speech was recorded remotely from the participants to measure the pitch ranges. Participants were requested to use their own microphones, often built into the device they were performing the experiment with, or into their headphones or earphones. They could test whether their microphones were working properly before starting their recording in the production task. Any speech recorded by the participant that was not related to the sample text they had to read, but for example consisted of them reading aloud the instructions too, was included for measurement.

The following method of F0 contour measurement was inspired by Deutsch (1990, 2004, 2009) and adapted. Each voice recording collected in the production task was measured and listed using Praat (Boersma & Weenink, 2023) software to determine F0 values for each 5-millisecond interval of speech, consulting the built-in filtered (ac) method. Any speech or sound preceding or succeeding the reading of the given text was disregarded for this analysis as to compare similar reference data. These resulting estimates were then plotted in a graph per each speech recording, reflecting occurrences of present spoken frequencies. The frequencies were represented per 5 Hz.

From this, an octave band containing the largest portion of speech samples was derived per participant. This octave band was then expressed by the two musical pitches representing the lowest and highest pitches of this octave range. Including the musical notation as these ‘semitone bins’ allowed for comparison between F0 range measurements and tritone paradox perception measurement, whilst also allowing for between-speaker comparison along a logarithmic scale. Such a scale is more representative of how pitch variation is perceived by the human ear (Hirst, 2021).

With the data from these individual measurements, average Dutch pitch contours were formed indicating generally at what frequencies Dutch participants speak in their native language. Male and female speech was not separated for this part, since the pitch range data was expressed in peak pitch classes instead of specific pitch heights. This data was then also compared to established literature pertaining to typical L1 pitch ranges of Dutch to validate the measurements (Collins & Mees, 2003; Deutsch, 1990, 1994; Willems et al., 1988).

Statistical Procedure

From the data resulting from the previously described measurements, four tests were conducted using Jamovi (2022), a statistical program which runs on R (2021). For a summary of these and their accompanying dependent and independent variables, please visit Table 3.

The first test was a Chi-Square (X^2) test of Association, assessing the group of Dutch participants and their individual perception patterns to explore the possibility of a general Dutch perception pattern. The same test was applied to investigate the connection between participants’ MET (Correia et al., 2021; adapted for Gorilla.sc from Wallentin et al., 2010) scores and their perception patterns to verify whether musicality could be related to someone’s perception of the tritone paradox. Thirdly, the relationship between a person’s vocal pitch range in L1 Dutch and their perception of the tritone paradox was measured. To test if a general Dutch pitch range was presented in the data, a Chi-Square Goodness of Fit Test was applied, comparing the F0 ranges and their frequency of occurrence. Finally, Chi-Square Test of Association was performed concerning the individual F0 ranges and tritone paradox perceptions to check for a relation between the two variables, regardless of the presence of a typical L1 Dutch pitch range based on the penultimate test.

Table 3

Summary of Statistical Tests and Relevant Dependent and Independent Variables

	Statistical Test	Dependent Variables	Independent Variables
Test 1	Chi-Square Test of Association	Occurrence frequencies	Tritone paradox perceptions (peak pitches)
Test 2	Chi-Square Test of Association	Tritone paradox perceptions	MET scores
Test 3	Chi-Square Goodness of Fit Test	Occurrence frequencies	F0 peak pitch ranges
Test 4	Chi-Square Test of Association	Tritone paradox perceptions (peak pitches)	F0 peak pitch ranges

Results

Tritone Paradox Perceptions

Firstly, to examine the linguistic effects of the tritone paradox and expand the existing literature, 29 Dutch participants completed the tritone paradox perception task, consisting of three blocks of 24 intervals. Figure 7 reflects the total distribution of perceptions of the tritone paradox by the Dutch group. The ‘perceptions’ in the horizontal axis are expressed in peak pitch classes, representing a participant’s orientation of the pitch class circle as derived from their judgements of the tritone paradox test. These can also be considered to represent someone’s perception pattern. As can be seen in Figure 6, two perception patterns (E-F, F#-G) were not yielded by the current dataset. The majority of participants (N=17, 58.62%) reflected a perception pattern with peak pitches between C-D, with the highest score for C#-D (N = 9, 31.03%). An example of an individual participant’s judgements to the tritone paradox and consequential pitch class circle with C#-D oriented at the top can be seen in Figure 9. This figure shows a graph representing the count of descending tritone judgements by participant hra687sl and their corresponding pitch class circle. As can be seen in the graph, this participant showed a particularly strong preference for hearing a tritone pair as descending in one order and as ascending in the opposite (e.g. A-D#/D#-A). This indicates a strong mental orientation of tones on one side of the pitch class circle as ‘higher’ compared to the other side, resulting in the circle on the right of Figure 10.

Figure 9

Total Distribution of Tritone Paradox Perceptions.

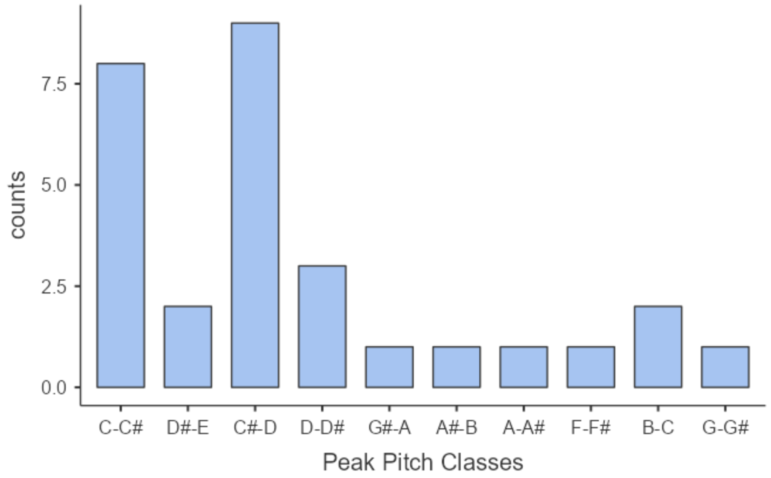
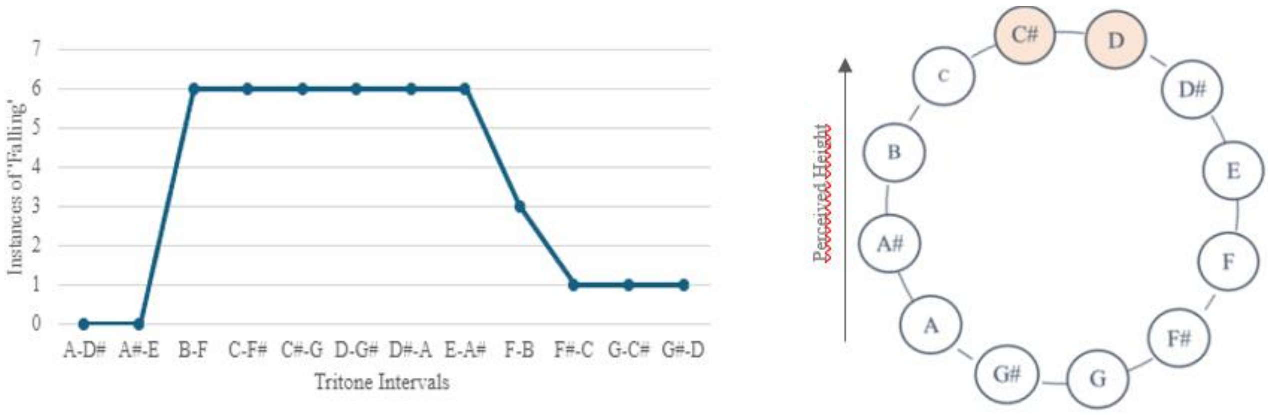


Figure 10

Tritone Interval Judged as ‘Falling’ by Participant ‘hra687sl’ on the left and Consequent Pitch Class Circle Orientation with C#-D as Peak Pitch Classes on the right.



The graph on the left illustrates the occurence distribution of intervals heard as ‘falling’, showing that the six pitch classes B, C, C#, D, D#, and E were heard as higher within their tone pairs most often. The figure on the right is derived from this trend, resulting in the peak pitch classes C# and D for this participant, as highlighted in orange.

Table 4
Proportions of Perceived Peak Pitch Classes

Level		Count	Proportion
C-C#	Observed	8	0.2759
	Expected	2.42	0.0833
C#-D	Observed	9	0.3103
	Expected	2.42	0.0833
D-D#	Observed	3	0.1034
	Expected	2.42	0.0833
D#-E	Observed	2	0.0690
	Expected	2.42	0.0833
E-F	Observed	0	0.0000
	Expected	2.42	0.0833
F-F#	Observed	1	0.0345
	Expected	2.42	0.0833
F#-G	Observed	0	0.0000
	Expected	2.42	0.0833
G-G#	Observed	1	0.0345
	Expected	2.42	0.0833
G#-A	Observed	1	0.0345
	Expected	2.42	0.0833
A-A#	Observed	1	0.0345
	Expected	2.42	0.0833
A#-B	Observed	1	0.0345
	Expected	2.42	0.0833
B-C	Observed	2	0.0690
	Expected	2.42	0.0833

Subsequently, a Chi-Square Goodness of Fit Test was conducted to examine whether the tritone paradox perception data would reveal any perception pattern for Dutch as a whole, as hypothesised earlier by the author. Table 4 represents the observed and expected distributions per perception pattern that were used in the performance of this statistical test. With an expected frequency count of 2.42, this test yielded a statistically highly significantly ($p < 0.001$) difference between the observed and the expected distribution of perception categories and Dutch participants, with X^2 (df =11, N = 29) = 40.1, p = 0.001. Particularly, these results indicated particularly notable differences between the observed and expected occurrences of peak pitch classes C-C# and C#-D for the Dutch participants, as yielded from the tritone paradox experiment.

MET Scores

Secondly, to examine the research question ‘To what extent can someone’s perception of the tritone paradox be attributed to their melodical musicality?’, MET scores were measured and compared with the perception patterns of the tritone paradox. Participants scored anywhere between 45% and 100% on the shortened MET, with a mean score of 72%. A distribution of the exact scores per participant can be seen in the summarised participant data in the detailed list in Appendix 2.

To test the hypothesis that musicality is not an influential factor for someone’s perception of the tritone paradox, a second Chi-Square Test of Association was performed, comparing the observed MET scores and the tritone paradox patterns, again expressed in peak pitches. To achieve this, the continuous MET scores were from percentages into three categorical bins by equal distribution into: low (0-46%), medium (55-64%), and high (73-100%) scores. No low scores were yielded amongst the participants. The distribution of categorical MET scores compared to perception patterns is represented in Table 5. The Chi-Square test did not show any statistically significant ($p < 0.05$) association between participants’ MET scores and the tritone paradox perceptions, $X^2(df = 9, N = 29) = 14.6$, $p = 0.102$.

Table 5

Distribution of Peak Pitch Classes Based on Tritone Paradox Perception per Observed MET Score

MET Score (Categorical)	Peak Pitch Classes										Total
	A-A#	A#-B	B-C	C-C#	C#-D	D-D#	D#-E	F-F#	G-G#	G#-A	
Low	0	0	0	0	0	0	0	0	0	0	0
Medium	0	0	0	4	7	0	0	1	0	1	13
High	1	1	2	4	2	3	2	0	1	0	16
Total	1	1	2	8	9	3	2	1	1	1	29

Dutch Pitch Range

Finally, the effect of the pitch range of speech on someone's perception of the tritone paradox was tested. To obtain these pitch range measurements, participants were requested to read aloud a pre-selected passage from Alice in Wonderland. The distribution of F0 range observations, as expressed by the pitch class pair representing the upper limit of someone's spoken octave band, is illustrated in Table 6.

The possibility of a typical Dutch pitch range based on the distribution of F0 data as observed in Table 6 was explored with a second Chi-Square Goodness of Fit Test. This test compared the frequency counts and the twelve possible F0 range categories. Considering an expected distribution count of 1.83, this Chi-Square test indicated that although the distribution of F0 ranges differs slightly among the participants, but not significantly ($p < 0.05$) so: $X^2(df = 11, N = 22) = 18.4$, $p = 0.074$.

To test the last hypothesis expecting that someone's individual vocal pitch range has an effect on their perception of the tritone paradox, a second Chi-Square Test of Association was performed comparing the individuals' F0 range measurements and their tritone paradox perceptions. A distribution of this comparison can be observed in Table 7. Based on this data, the Chi-Squared test did not yield a significant ($p < 0.05$) relationship between someone's spoken pitch range and their perception of the tritone paradox, $X^2(df = 64, N = 22) = 73.5$, $p = 0.194$.

Table 6

Distribution of F0 ranges

F0 Range (Category)		Count	Proportion
C-C#	Observed	3	0.1364
	Expected	1.83	0.0833
C#-D	Observed	4	0.1818
	Expected	1.83	0.0833
D-D#	Observed	1	0.0455
	Expected	1.83	0.0833
D#-E	Observed	2	0.0909
	Expected	1.83	0.0833
E-F	Observed	4	0.1818
	Expected	1.83	0.0833
F-F#	Observed	0	0.0000
	Expected	1.83	0.0833
F#-G	Observed	1	0.0455
	Expected	1.83	0.0833
G-G#	Observed	0	0.0000
	Expected	1.83	0.0833
G#-A	Observed	1	0.0455
	Expected	1.83	0.0833
A-A#	Observed	0	0.0000
	Expected	1.83	0.0833
A#-B	Observed	5	0.2273
	Expected	1.83	0.0833
B-C	Observed	1	0.0455
	Expected	1.83	0.0833

Note: F0 range measurements from speech were expressed as pitch class pairs representing the upper limit of someone’s octave band including the largest portion of vocal frequencies.

Table 7

Distribution of Tritone Paradox Perceptions per F0 Range Category

	Tritone Paradox Perceptions									
F0 Range Categories	**C-C#**	**D#-E**	**C#-D**	**G#-A**	**A#-B**	**D-D#**	**F-F#**	**B-C**	**G-G#**	**Total**
A#-B	1	0	2	1	0	0	0	0	1	5
E-F	1	1	2	0	0	0	0	0	0	4
D#-E	0	0	1	0	0	0	1	0	0	2
F#-G	0	0	0	0	1	0	0	0	0	1
D-D#	1	0	0	0	0	0	0	0	0	1
C-C#	0	0	1	0	0	0	0	2	0	3
C#-D	1	0	1	0	0	2	0	0	0	4
G#-A	1	0	0	0	0	0	0	0	0	1
B-C	0	0	1	0	0	0	0	0	0	1
Total	5	1	8	1	1	2	1	2	1	22

Discussion

This current thesis aimed to contribute to the body of literature on the tritone paradox by exploring the effects of someone's musicality and linguistic background on their perception of the auditory illusion. Specifically, this study focussed on participants who had been born and grown up in the Netherlands, speaking Dutch as a first language, to investigate the theory brought forward by Deutsch et al. (1991) that someone's pitch range in speech is related to how they interpret the tritone paradox. In order to research this, the following research questions were proposed:

1. How do native Dutch listeners perceive the tritone paradox?
    a. How does this compare to what is known about Californian English and Southern British English listeners?
2. To what extent can someone's perception of the tritone paradox be attributed to their melodical musicality?
3. To what extent can someone's perception of the tritone paradox be attributed to their personal pitch range?

a. To what extent can a native Dutch person's perception of the tritone paradox be attributed to typical L1 pitch range?

Tritone Paradox Perceptions

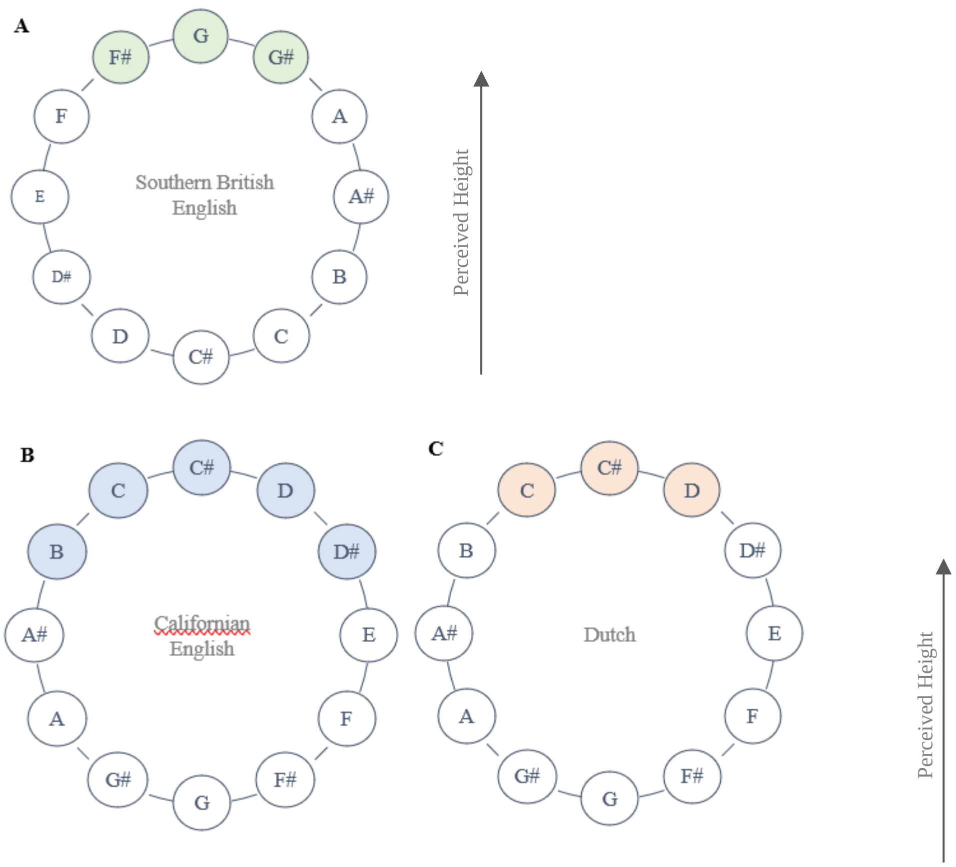
The first main and subordinate research question were investigated through the Dutch participants' response rates to the tritone paradox task in this study's online experiment. Based on earlier findings by Deutsch (1990, 1994, 2007) and Deutsch et al. (1991) which yielded significant perception patterns based on a participant's area of upbringing and subsequent language experience in childhood, it was expected that native Dutch listeners of the tritone paradox would also perceive the tritone paradox similarly amongst each other. Therefore, tritone interval judgements of each participant was converted into a personal perception pattern, as expressed by the pitch class pair that would present itself at the peak of their pitch class circle orientations. An example of such a judgement set and subsequent pitch class circle orientation could be seen previously in Figure 10, representing the C#-D peak pattern yielded from participant hra687sl.

When comparing frequency counts of the collected tritone perception patterns within the group of Dutch participants (N=29), the distribution of counts per perception pattern was highly significantly ($p = 0.001$) unbalanced. This implied a preference within the overall Dutch participant population towards certain perception patterns over others. Specifically, patterns under C-C# and C#-D were represented much more often than the others (8 and 9 tokens, respectively). Based on these results and the theory of pitch class circle orientation derived from tonal perception, it could be assumed that native Dutch listeners of the auditory illusion are likely to react to the tritone paradox in a similar manner and seem to subconsciously 'hear' the pitch classes C, C# and D as higher than the other pitches in the western musical scale.

Furthermore, when comparing the perception pattern of the Dutch participants to those of the CA and SBE groups by Deutsch (1994), it was expected that the Dutch perception of the tritone paradox would be more similar to that of the CA group, as compared to the SBE group. The observed results confirm this hypothesised pattern comparison, as illustrated by Figure 11. It shows the opposite CA (A) and SBE (B) patterns found by Deutsch, corresponding to pitch class circles oriented under B-D# and F#-G#, respectively, and the novel Dutch (C) perception pattern expressed by the peak pitch classes C-C#-D. Dutch listeners of the tritone paradox generally have a similar, although narrower, interpretation of the tritone paradox intervals as Californian listeners, and a completely opposite interpretation than listeners from the south of England. In other words, a Dutch or Californian person is likely to hear the interval G-C# as ascending whilst someone from the south of England would hear that identical interval as descending. Therefore, to answer the first set of research questions: native Dutch participants generally perceive the tritone paradox similarly amongst each other, often hearing at least the tritone intervals B-F, C-F#, C#-G, and D-G# as descending and their counterparts as ascending, which is relatively similar to the Californian pattern and the absolute opposite from the English pattern yielded by Deutsch.

Figure 11

Three Pitch Class Circles of A) Southern British English, B) Californian English, and C) Dutch Listeners, as Derived from Their Perception Patterns of the Tritone Paradox



MET and the Tritone Paradox

Secondly, aside from collecting and assessing the perceptions of the tritone paradox, the experiment this study conducted also indexed the participants' musicality to investigate this as a potential influence explaining why one person might hear the pitch of a tritone interval move in one direction, and someone else might hear it in the opposite way. Since musical skill has been rejected previously as an influential factor (Deutsch et al, 1987), musicality was not expected to affect perception patterns of the participants in this study. Nevertheless, for the sake of academic verification and updating the current body of literature, musicality was included in the analysis of interpersonal factors that contribute to someone's perception of the tritone paradox.

Therefore, participants were offered an adapted version of the MET (Wallentin et al., 2010) in their own language, which score would represent their auditory ability to recognise complex melodical information. This approach differed from Deutsch (1986, 1987) and Deutsch et al. (1978) in how the degree of musicality was not measured in musical training (or lack thereof), but in pitch perception accuracy. Participants were presented with an eleven-trial identification task where they listened to two successive melodies and had to judge whether they were hearing two identical or different melodies. The subsequent score was later categorised into either Low, Medium, and High and compared to the participants' tritone paradox perception pattern. As expected, this study did not find support for the effect of musicality on someone's perception of the tritone paradox ($p = 0.102$), additionally validating the earlier similar findings by Deutsch et al.

Nevertheless, what could still be interesting to investigate in a subsequent study, would be how people with lower MET scores or even established amusia would react to the tritone paradox. Current literature including this study have only focussed on the effect of musicality with the focus of what the acquisition of musical training or skill, as compared to an 'average' person would contribute to our perceptions of the tritone paradox, but it is still unknown whether the tritone paradox would still hold its effect size on amusical listeners. If this would be the case, it could provide further evidence that having a 'touch' for musicality would in no way interact with our perception of the illusion, giving way to other explanations for our diverse interpretations of the intervals, such as language varieties.

F0 Range and the Tritone Paradox

Finally, the last main and subordinate research questions that were introduced at the end of the background section pertained to the effect of participant's individual pitch range on their perception of the tritone paradox, and the degree in which a typical Dutch pitch range could be determined as a factor of influence on the Dutch perception pattern of the auditory illusion. Based on data and expectations surmised by Deutsch (1990, 1994, 2007), Deutsch et al. (1991, 1994, 2009) and further limited (contemporary) literature available comparing typical Dutch pitch range to that of SBE and CA (Collins & Mees, 2003; Willems, Collier & 't Hart, 1988), it was hypothesised that someone's tritone paradox perception (as expressed in peak pitches) would in turn reflect their peak pitch ranges in speech, and that a general Dutch pitch range could be derived from the speech recordings and would correspond to the general Dutch perception pattern of the illusion.

To examine this, participants were asked to record their voices whilst reading aloud a short passage of text from Alice in Wonderland (Caroll, 1866, 1948). Due to technical faults and other unknown reasons, recordings could not be recorded from every participant. For that reason, the analysis for this part was conducted for only 22 participants from the original 29. From their speech, F0 values were drawn for every 5ms interval and collected in a graph representing their pitch frequencies in bins per 5 Hz. The largest portion of F0 counts were converted into an octave band, of which the pitch class pair including the upper limit was used to represent someone's pitch range of speech.

Contrary to expectations formulated earlier in this paper, a Chi-Square Goodness of Fit test the Dutch participants did not portray any significantly specific pitch range category ($p = 0.074$). Although, as could be seen in Table 4, some pitch ranges were more common than others, but these were too randomly distributed along the musical scale to draw any conclusions about a typical Dutch F0 range. Moreover, on an individual level, the data did not suggest that someone's peak pitch classes in speech could be correlated to their peak pitch ranges in auditory perception ($p = 0.194$). This finding contradicts earlier studies that yielded strong implications for the linguistic effect of pitch range on the tritone paradox.

Nevertheless, the results discussed at the beginning of this discussion chapter would still suggest the possibility of linguistic influence. The way in which the Dutch tritone paradox perception pattern was expected to arise, namely more similarly to the previously established CA pattern than to the SBE pattern, was based solely on literature that suggested that both Dutch and General American have a narrower and lower pitch range than British English. Since it is entirely possible that there are various other linguistic features than pitch range alone (e.g. speech tempo, tonal versus non-tonal, intonation patterns, etcetera) that would reveal Dutch as more closely related to American English than to British English, the striking relationship between the perceptive behaviour of the two language groups could imply that the tritone paradox might be linguistically motivated after all. The specific characteristic that can be attributed to this relationship, however, might just not be pitch range. Further research focussing on a broader spectrum of potential linguistic traits shared by Dutch and CA as compared to SBE is advised to investigate the validity of these implications brought to light by the current set of outcomes.

Another probable reason for the unexpected outcome pertaining to the pitch range effects on someone's perception of the tritone paradox could also be sought methodologically. As mentioned previously, the reference text which participants were requested to read aloud for the speech production task was from an excerpt in Alice in Wonderland by Lewis Caroll. It was chosen because the experiment was originally aimed at both native speakers of Dutch and SBE, with the intention that the reference text would be as similarly as possible in both languages for valid pitch range measurements. Because Alice in Wonderland is such an internationally popular story, it has accumulated many translations, making it a convenient candidate for finding versions in both English and in Dutch that are textually highly similar.

Further Limitations and Recommendations

Additionally, the online experiment was experienced as quite lengthy and taxing for unpaid voluntary remote participants during the pilot phase, due to the necessary inclusion of a questionnaire, standardised tests, perception task and production task. Therefore, in an attempt to satisfy the participatory experience with the goal of attaining as many participants as possible, it was decided that such a recognisable work of popular fiction would be preferred over a neutral but more dull text, such as from a manual. In retrospect, the latter might actually be preferred as to not spark a more ‘narrating voice’ in a portion of the participants, automatically displaying overly exaggerated intonation as if they were reading to a child. Evidently, such manner of speaking does not reflect someone’s general pitch range, which this analysis effectively aimed at.

Thus, a recommendation for a replicatory study would be to measure and test for F0 range of Dutch in both free speech and read speech from a more neutrally toned source text. If this would indeed influence the pitch range to be more uniform for the entire Dutch participant population, it is anticipated that the relationship between someone’s pitch range and their perception of the tritone paradox is stronger than presented by this current study.

Furthermore, due to the participant population size, the current study could not investigate the influence of regional dialect differences in pitch range between different variations of Dutch. As can be seen in Appendix II, the participants were distributed across most of the Dutch provinces (9 out of 12), but the participant frequencies per province were too unbalanced and small to perform any meaningful tests that would explore potential regional effects to someone’s pitch range in Dutch speech. For that reason, the Dutch pitch range examined in this study represented a collection of every recorded dialect in the participant population instead of taking regiolect approach, such as was done for English. The participant population size and subsequent broad linguistic scope could provide yet another explanation for this study’s inability to conclude a typical L1 Dutch pitch range, as there might be regional differences that are simply too far apart to be unified significantly. This further supports the recommendation to replicate the current study with a focus on a larger and more balanced participant population.

A final addition to this advice would be to make another attempt at collecting novel data from South British English and/or Californian American English speakers, so that a comparison between the perception patterns and pitch ranges from the discussed language variations can be validated using raw data rather than to partially rely on secondary data. An added benefit of this approach would be the ability to detect if there may have been any shifts between present tritone paradox perception and speech patterns, and those from roughly thirty years ago, considering the changeable nature of spoken language.

One approach to reaching a wider and more equally distributed participation population can be sought in the improvement of the online instrument used for the experiment conducted in this study, or the transfer to another platform than that was currently used. Aside from the initial challenge to recruit SBE participants for a study based in the Netherlands, the online experiment platform conducted by this study suffered from too many technical issues, as addressed by a number of participants, which could not always be guided or solved by the researcher. This caused a large drop-out rate of participants from both languages and lead to the eventual exclusion of English data altogether.

These technical issues also represent itself in the data size difference between the perception task and the production task. Some participants reported not being able to continue to the next page, regardless of the device type, internet provider or browser they were using. Others experienced problems with the automated recording process, which could not be monitored or solved during the course of an experiment trial by either the researcher nor the participant, such as delayed initiation of the recording halfway through the task, inability to save the recording, or the storing of an empty recording file. Considering that 98 Dutch speaking and 19 English speaking participants had initially started the experiment, of which merely 22 native Dutch participants eventually successfully completed the experiment, it is expected that this drop-out rate could be decreased with either an improved version of the Gorilla Experiment Builder or another online experiment platform. It should be noted that at the time of the current experiment, the audio-recording feature in Gorilla.sc was still in its beta stage, whilst other online experiment building platforms such as Qualtrics did not offer this feature at all. Therefore, with the overall goal to reach a larger population both country-wide and overseas, and to strive towards a lower drop-out rate of participants reached, it is advised to carefully select and test various online experiment building platforms before creating and launching the reproduction experiment.

Conclusion

This present study aimed to help uncover the mysteries behind the auditory illusion of the tritone paradox. As the illusion’s creator Diana Deutsch found, upon listening to the same tritone interval, listeners disagree amongst each other whether they hear the two tones rise or fall. Taking inspiration from Deutsch's research on the role of L1 experience from childhood on our perception of complex tones, this study focussed on the perceptive behaviour of the tritone paradox by native Dutch listeners, as compared to what was already known on the perception and speech patterns of Californian American and Southern British English participants (Deutsch, 1990, 1994; Deutsch et al. 1991). To do this, 29 Dutch remote participants completed an online background survey, musicality indexation test, tritone paradox perception experiment and speech recording task.

Five hypotheses were formed based on the established literature on the interactions between language experience, musicality, and the tritone paradox, and typical pitch ranges of Dutch, SBE and CA. Namely, it was expected that a) Dutch listeners of the tritone paradox would reflect a collective perception pattern which would be more closely related to the CA pattern than to the SBE pattern; b) that someone's level of musicality would not influence their perception of the tritone paradox, but that c) someone's native language background would have an effect, which would be found in the similarity of the pitch class pair delimiting someone's spoken pitch range and the peak pitch class pair representing their tritone paradox perception pattern. The findings of this current study supported the first three of these hypotheses, portraying a Dutch tritone paradox perception pattern that is similar to the Californian pattern, but opposite to the English pattern, and unrelated to someone's musicality. The peak pitches found in this pattern are C-D, whereas the Californian are B-D# and those in the English pattern are F#-G#, indicating that someone who has grown up in the Netherlands or California is likely to hear a complex tone pair from the tritone paradox such as C#-G as descending, whereas someone from the south of England would hear it as ascending. Considering that this Dutch perception pattern was expected based on the comparison of typical L1 pitch range patterns found in established literature (Collier & 't Hart, 2003; Deutsch, 1994), it is still expected that someone's language experience interacts with their perception of the tritone paradox, even though the present findings might not directly support this theory in its entirety.

Therefore, it is recommended to replicate this study to further validate or falsify the existing theory on this language-music connection. This can be achieved with a larger and more regionally balanced collection of participants, and an improved method of collecting speech samples that provoke a more neutral tone and more natural manners of speaking. Doing so would allow the pitch range analysis method to be more representative of people's typical use of their native language in conversation, expectedly resulting in pitch range measurements that can be categorised better according to language variety and offer more conclusive support for or against the proposed theory. This methodological recommendation, along with the novel revelations on the Dutch perception pattern of the tritone paradox presented by this current study, is hoped to contribute to unravelling the mystery of the great psychoacoustic curiosity known as the tritone paradox.

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Appendix I.I *Consent form and Questionnaire (English)*

Consent Form

For the research on the tritone paradox, it is necessary to use your personal data. This data shall be collected by the means of your responses to the questionnaires and tasks in this experiment. To use this data during our research we need your consent. Participating in this research will be entirely voluntary and your data will remain anonymous. You may decide at any moment to quit participation.

Your name, contact information or any other data that could be traced back to your identity will not be saved.

If you may have questions or remarks regarding the contents of the experiment or the study, please contact m.c.b.blom@umail.leidenuniv.nl

I have read and understood the above and hereby give my consent to take part in this experiment in full knowledge that data is being recorded: I Agree. [button]

Questions:

1. What is your age? (open)
2. What is your gender?
    a. Female
    b. Male
    c. Non-binary
    d. Other (please specify) (open)
3. What is your place of birth? (open)
4. What region did you grow up in when you were a child? (open)
5. Do you have any hearing impairments? (multiple options)
    a. No
    b. Hearing loss in one ear
    c. Symmetrical hearing loss in both ears
    d. Asymmetrical hearing loss in both ears
    e. Tinnitus

    f. Other, namely… (open)

6. How much does this affect your hearing? (Likert)
    a. I cannot hear any sound. [0, 1, 2, 3, 4, 5] I can hear (practically) anything.
7. Do you have any speech impairments?
    a. No
    b. Yes, namely… (open)

Appendix I.II *Consent form and Questionnaire (Dutch)*

Consent Formulier

Voor het onderzoek over de tritone paradox is er persoonlijke data nodig. Deze zal worden verzameld aan de hand van jouw reacties op de vragenlijsten en de experiment onderdelen. Om deze data te gebruiken voor het onderzoek, hebben we jouw toestemming nodig. Meedoen aan dit onderzoek blijft strikt vrijwillig en persoonlijke data zal anoniem zijn. Je kan op elk moment besluiten te stoppen.

Je naam, contactgegevens of andere gegevens die jouw identiteit kunnen herleiden, zullen niet worden opgeslagen.

Eventuele vragen of opmerkingen kunnen terecht bij m.c.b.blom@umail.leidenuniv.nl.

Ik heb bovenstaande informatie gelezen en begrepen en geef mijn consent voor het gebruik van data voor dit onderzoek: Ik geef toestemming [button].

Questions:

1. Wat is je leeftijd? (open)
2. Wat is je gender?
    a. Vrouw
    b. Man
    c. Non-Binair
    d. Anders, namelijk: (open)
3. Wat is je geboorteplaats? (open)
4. In welke regio ben je als kind opgegroeid? (open)
5. Heb je last van gehoorproblemen? (multiple options)
    a. Nee
    b. Gehoorverlies aan één oor
    c. Symmetrisch gehoorverlies aan beide oren
    d. Asymmetrisch gehoorverlies aan beide oren
    e. Tinnitus
    f. Anders, namelijk… (open)

6. Hoe goed is je gehoor? (Likert)
    a. Ik hoor niks. [0, 1, 2, 3, 4, 5] Ik hoor (vrijwel) alles.
7. Heb je last van spraakproblemen?
    a. Nee
    b. Ja, namelijk…

Appendix II *Participant Data*

Participant ID	Gender	Age	Childhood Province	Hearing	MET Score	Tritone Peak Pitches	F0 Peak Pitches
0dp3i1o5	Woman	28	Noord-Brabant	0	64	C-Cis	x
2b5086kn	Woman	56	Noord-Brabant	Symmetrical hearing loss to both sides, tinnitus	55	C-Cis	Ais-B
2gghvc3x	Woman	21	Friesland	Tinnitus	73	Dis-E	E-F
3q87c5b7	Woman	25	Drenthe	Asymmetrical hearing loss, tinnitus	64	Cis-D	Dis-E
3qqoqf7r	Woman	25	Utrecht	0	73	D-Dis	x
501t5eeq	Woman	33	Noord-Brabant	0	55	Gis-A	Ais-B
6n24ouwl	Woman	26	Gelderland	0	64	Cis-D	E-F
78phykve	Man	24	Utrecht	0	82	Ais-B	Fis-G
8y0l2fjw	Woman	32	Groningen	0	73	C-Cis	D-Dis
9fy5szzz	Woman	23	Noord-Brabant	0	55	Cis-D	C-Cis
9qy27904	Woman	56	Noord-Brabant	0	73	C-Cis	Cis-D
feasgc45	Woman	43	Noord-Brabant	0	100	C-Cis	Gis-A
g4z9xl9c	Woman	20	Friesland	0	64	Cis-D	x
gf5qrskk	Nonbinary	x	Groningen	0	82	D-Dis	Cis-D
hra687sl	Woman	24	Overrijssel	Tinnitus	73	Cis-D	Cis-D
ixzebsje	Woman	22	Noord-Brabant	0	64	Cis-D	E-F
l29r62po	Woman	25	Overrijssel	0	82	A-Ais	x
la59buja	Man	25	Zuid-Holland	0	64	C-Cis	E-F
n5ythm2k	Woman	30	Noord-Brabant	0	91	Dis-E	x
q59hz11z	Woman	21	Noord-Holland	0	55	F-Fis	Dis-E
qoi8tw73	Woman	68	Utrecht	0	82	C-Cis	x
t5hsm0es	Woman	25	Zuid-Holland	0	64	Cis-D	Ais-B
t9vbgyes	Woman	20	Groningen	0	91	B-C	C-Cis
wwvtq0f1	Woman	62	Noord-Holland	0	55	Cis-D	Ais-B
xe8qqp8w	Woman	20	Friesland	0	82	D-Dis	Cis-D
y7tcx78y	Woman	20	Drenthe	0	73	G-Gis	Ais-B
y9ai7fim	Man	55	Zuid-Holland	0	91	B-C	C-Cis
yhae3tab	Woman	28	Noord-Brabant	0	82	Cis-D	B-C
zn6duuoh	Man	26	Drenthe	0	64	C-Cis	x

Note: where the data is represented by ‘x’, there was no information collected from the participant on that particular topic.