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# Effects of learning on dissonance judgments

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**Background in music cognition:** A frequently posed question regards the origins of the aversion most listeners have to dissonant sounds. In the domain of psychology, attempts to address this question have included examining how early similar biases may be found in infants as well as whether they exist at all in non-human species. In contrast, another line of work has, rather than focusing on potential biological predispositions, examined the specific role that musical exposure and training may play in driving emotional judgments of dissonance.

**Background in music history:** Speculation as to why consonant sounds are preferred to dissonant sounds dates back many centuries to the ancient Greek notion that beauty is intrinsically related to proportions. More recently, the prevailing theory is that sensory dissonance arises as a result of mechanical interference within the organ of hearing, although another plausible theory states that consonance preferences are driven by a preference for harmonicity.

**Aims**: The current review aims to re-examine the direct evidence that may be found for a role of learning mechanisms in dissonance processing, and in doing so inform theories of dissonance perception. It also seeks to stimulate thinking about the evolution of polyphony: specifically, the role of exposure and learning on the perception of dissonance from the beginning of the second millennium when polyphonic music began to emerge.

**Main contribution**: We highlight, in turn, the effects of exposure and more intentional forms of learning on the modulation of responses to dissonance. We demonstrate that the notion that learning plays a role in emotional judgments of dissonance finds converging evidence in a range of studies using numerous different methodological approaches. In doing so we show the relevance of complementary methodologies from psychology and affective neuroscience in addressing an age-old question.

**Implications**: By providing compelling evidence in support of a role of learning processes in dissonance processing, the current review supports the re-examination of harmonicity as a viable driver of emotional responses to dissonance and further suggests that a parsimonious theory of dissonance should incorporate learning and memory processes. Finally, it provides a framework with which to consider the changes in music seen over the ages with respect to the composers' use and the listeners' reception of 'dissonance'.

**Key words:** Dissonance, consonance, learning, memory, mere exposure effect, musical training

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## Introduction

The experience of dissonance is an important part of music listening. The current review is motivated by the notion that seeking to understand mechanisms that contribute to this experience is, therefore, an important endeavour. The review makes a distinction between the initial sensation that leads one to describe a sound as pleasant or unpleasant often referred to as 'sensory dissonance' (Plomp & Levelt, 1965; Terhardt, 1974), and 'musical dissonance' which is generally related to judgments of a sound's pleasantness or unpleasantness in a musical context (Cazden, 1980). While sensory and musical dissonance are known to be intrinsically related, the former often being used to the service of the latter (Meyer, 1956), the current review focuses on sensory dissonance (and consonance) i.e. the sense of unpleasantness (or pleasantness) that accompanies a single chord, and in particular the origins of the aversion (and preference) that most listeners have for such chords. In addition to this focus on responses to chords in isolation, the review also addresses the fact that the musical context in which a given sound is presented can and does affect listeners' perception of its relative dissonance and shows that here, perhaps even more than for the perception of a chord in isolation, learning and enculturation play important roles. The common definition of sensory dissonance, as an unpleasant sensation induced by the simultaneous presentation of two sounds, does not provide a mechanistic account of the phenomenon although it is effective in emphasising and making explicit an important point: namely, the tendency for a 'dissonant' sound to evoke a negatively valenced emotion (Costa, Ricci Bitti, & Bonfiglioli, 2000; Plomp & Levelt, 1965; Wedin, 1972). We argue that this defining aspect of dissonance makes its study relevant not just to those interested in the perception and categorisation of auditory stimuli, but also to the study of factors that may drive emotional responses to such stimuli.

Speculation as to why dissonant chords generally produce more negative valence judgments than consonant chords dates back many centuries, starting with the ancient Greek notion that beauty is intrinsically related to proportions. Pythagoras proposed that consonance arises when there is a simple ratio in the lengths of simultaneously sounding strings while in contrast a sound will be dissonant if it is produced by strings with lengths that form complex ratios. However, contemporary accounts emphasize the fact that sounds from musical instruments are comprised of multiple discrete frequencies.

Perhaps the most popular theory regarding the origins of dissonance suggests that it arises from mechanical interference within the organ of hearing. Specifically, this theory posits that the unpleasantness that is experienced on listening to dissonant chords is due to a phenomenon known as beating. It was Helmholtz (1870) who first noted that dissonant chords like the minor second, which produce frequencies that are close but not identical, result in beating while, in contrast, consonant chords, which have frequencies that are widely spaced do not. Today, it is well understood that dissonant chords contain frequency components (harmonics) that by virtue of being too closely spaced cannot be resolved by the cochlea. The shifting in and out of phase of these frequency components, which lie in the same cochlear critical bandwidth (Greenwood, 1991), results in a modulation of the amplitude of the waveform. Crucially, beating is said to occur when the auditory nerve transmits these amplitude modulations up the auditory system resulting in a perception of auditory roughness in the listener (Plomp & Levelt, 1965).

Helmholtz also argued that the sensation of roughness is at a maximum when two frequencies beat at a rate of 35Hz; however, new generations of psychoacousticians have since refined these notions (Hutchinson & Knopoff, 1978; Kameoka & Kuriyagawa, 1969; Plomp & Levelt, 1965; Rakowski, 1982). For instance, Plomp and Levelt (1965) designed a function for assessing the relative dissonance of two pure tones, based on where their frequencies fall within a given bandwidth. They showed that the critical bandwidth which determines whether notes will beat or not, is not stable, as suggested by Helmholtz, but depends on the mean frequency of the component tones. Today, the notion that beating and roughness drives aversion for dissonance has found support in a number of studies suggesting that listeners find beating unpleasant (Plomp & Levelt, 1965), that listeners prefer chords without beats to those with beats (McDermott, Lehr & Oxenham, 2010) and that beating in a chord can provide a feeling of tension in tonal (Bigand, Parncutt & Lerdahl, 1996) as well as in non tonal music (Pressnitzer, McAdams, Winsberg & Fineberg, 2000).

While Helmholtz (1870) based his theory of consonance and dissonance on both the physiological properties of the ear and the physical qualities of tones, another approach would place more emphasis on the cognitive aspects of the experience of dissonance. Carl Stumpf (1883) would speak of the 'apperception'[i] of tones rather than their 'perception', where apperception emphasises evaluation in terms of previous experience. Stumpf challenged the notion that dissonance arises from the failure of upper partials to align pointing out that pure tones can also create the sense of dissonance even without harmonics. Based on a seminal experiment, in which he presented subjects with single tones and dyads and required them to indicate whether they heard one tone or two, he proposed that perception of consonance and dissonance is better distinguished in terms of tonal fusion (or *Verschmelzung)*. He argued that those dyads which subjects tended to mistake for a single tone are the intervals prone to tonal fusion and that these stimuli which bring tonal fusion, have the perceptual quality of consonance.

Stumpf would later abandon his own theory due to a concern that tonal fusion is a consequence rather than a cause of the mechanisms underlying consonance judgments and due to a growing belief that Helmholtz's acoustics and physiology approach provided a more comprehensive account (Stumpf, 1926). However, another theory based on the notion of fusion still holds a degree of credibility today. In its basic form, this theory states that the feeling of unpleasantness that listeners report in response to dissonance is less driven by an early cochlear mechanism than by the perception of harmonicity. Harmonicity, which describes the fit of a sound's spectrum with a single harmonic series (Gill & Purves, 2009) is closely related to Stumpf's notion of fusion (as the degree to which multiple pitches are heard as one). According to the theory of harmonicity, consonant chords share a lot of harmonics in common and therefore sound pleasant while dissonant chords share very few harmonics in common and thus result in a feeling of unpleasantness (DeWitt & Crowder, 1987; Ebeling, 2008; Tramo, Cariani, Delgutte & Braida, 2001). The theory has gained support from experiments that show that consonant judgments are generally always obtained as long as tones have coincident partials (Bidelman & Krishnan, 2009; Slaymaker, 1970). It continues to receive attention in light of psychophysical evidence that suggest a precedence, in bringing about consonance and dissonance judgments, of the presence of coincident partials over the presence of roughness (Cousineau, McDermott, & Peretz 2012; McDermott et al., 2010). McDermott et al (2010) noted that the reason it had been difficult to distinguish between the theories of beating and harmonicity is that beating and harmonicity tend to occur together. However, recent advances in synthetic stimuli (or sound synthesis) allow the two sound properties to be studied in isolation. The authors showed that in a large group of participants (almost 300 subjects) the degree of preference for harmonicity correlated with consonance, whereas the degree of aversion to beating did not. McDermott et al (2010) took the result to suggest that preference for harmonicity and not an aversion to beating drives the preference that most listeners show for consonant relative to dissonant chords. However, perhaps even more pertinent to the current review, the authors also revealed an important link between preference for consonance and musical exposure or training, by showing a relationship between both harmonicity and consonance and the number of years subjects had spent playing a musical instrument. More recent work in which those with a disorder of musical listening known as congenital amusia failed to show a preference for consonance over dissonance, and also for harmonic over inharmonic tones while showing normal preference for stimuli without beating (compared to those with beating) has been taken as further evidence of the relationship between consonance and harmonicity (Cousineau et al, 2012).

Other work has sought to describe sensory consonance and dissonance by addressing the role of additional auditory attributes (Terhardt, 1974), with for instance one model proposing sensory consonance to be a product of four psychoacoustic quantities that include loudness, sharpness and tonalness in addition to roughness (Aures, 1985a; Aures, 1985b). However, regardless of which approach or theory provides the most accurate account of dissonance, we may note that dissonance is, in any case, both an acoustical and emotional phenomenon. A frequently posed question is whether the origin of preference for sensory consonance or conversely aversion to dissonance is innate or learned or both. In this paper, we first describe literature that was initially taken to suggest that responses to dissonance are innate before reviewing the increasing literature that suggests that learning plays an important role in such responses.

## 1. The question of the origins of consonance preferences

Developmental psychologists have attempted to address the question of the origins of consonance preferences by assessing how early these biases may be found in infants and therefore the extent to which emotional responses to dissonance may be said to be innate. Based on much evidence that *looking time* is a good measure of affective responses as well as attentional preferences, these studies used relative looking time to consonant versus dissonant intervals as a measure of infants' preferences. In doing so, they revealed that infants show a preference for consonant relative to dissonant music from a very early age (Schellenberg & Trainor, 1996; Schellenberg & Trehub, 1996a; Schellenberg & Trehub, 1996b; Trainor & Heinmiller, 1998; Trainor, Tsang & Cheung, 2002; Zentner & Kagan, 1996; Zentner & Kagan, 1998). These findings of a very early preference for consonance led many experimenters (e.g. Schellenberg & Trainor, 1996; Zentner & Kagan, 1998) to suggest that sensitivity to sensory consonance and dissonance is based on processing predispositions and innate preferential biases.

The majority of the studies using the looking time technique were carried out on older babies of up to several months (e.g. 2, 4, 6, 7, 9 months, 6 years), thus, leaving open the question of the role of effects of exposure at the point of testing. Nonetheless, the notion of innate preferences seemed to receive further support in another study testing babies as young as 2 days old (Masataka, 2006). It is remarkable to observe that consonance preferences were also observed here in infants at such an early age. However, once again, the issue of exposure remained a problem. Given that the late-term human foetus has a functioning auditory system, extra-uterine auditory stimulation (whereby the foetus is exposed to externally produced auditory stimuli while still in the womb) may take place even before an infant is born (Fifer & Moon, 1995). Thus, even in a study testing 2-day old babies like that from Masataka (2006) it remains possible that by the point of testing, these babies had already received adequate exposure to consonant sounds to drive their preference for it.

Another group of studies which sought to explore the biological basis for consonance preferences carried out tests on non-human species to see if they, like humans, would show any biases. Borchgrevink (1975) designed a test chamber in which when a rat pressed one pedal a consonant chord was heard, while pressing the other pedal elicited a dissonant chord. He observed that after 3 weeks of 15 minutes a day in the test chamber, rats appeared to show a preference for consonance as defined by the difference between the number of times they pressed on each of the pedals. In a similar study carried out in birds, European starlings were presented with chords comprised of three simultaneous complex tones and were trained to peck at one key when a consonant chord was presented and at another when a dissonant chord was heard (Hulse, Bernard, & Braaten, 1995). The authors observed that the chicks were able to generalize the distinction between consonance and dissonance to new pairs of consonant and dissonant chords they were presented with. A number of more recent studies have confirmed that non human species including Japanese monkeys, Java sparrows and pigeons, can discriminate between consonant and dissonant sounds (Brooks & Cook, 2010; Izumi, 2000; Watanabe et al, 2005) while preferences for consonant over dissonant sounds have been shown in chicks and in an infant chimpanzee (Chinadetti & Vallortigara, 2011; Sugimoto et al., 2010).

The conclusion that was drawn from many of the animal studies is that sensitivity to sensory consonance might be a fundamental characteristic of auditory perception across species. However, as in the infant studies, such conclusions are debatable as there exists a potential confound of exposure. Specifically, even in those studies where animals were carefully protected from exposure to consonance before testing (e.g. Sugimoto et al., 2010), there remains the issue that animals were exposed to the consonant sounds they themselves produced. Indeed, in one study in which this was not a possibility, as the animal in question (the tamarin monkey) did not produce such vocalisations, preferences for consonance were not reported to be present (McDermott & Hauser, 2004) although the animals were able to differentiate the two types of sounds.

Given the limitations of infant and non human species research, one might look to the examination of dissonance responses across cultures as a promising tool to determine the universality of these judgments. However, such studies have provided inconsistent results. Butler & Daston (1968) showed that consonance judgments were similar in American and Japanese listeners while work from Maher (1976) would later suggest that consonance judgments are different in Canadians and Indians, with the latter showing greater tolerance toward dissonant intervals. Unfortunately, the cross cultural approach is increasingly less feasible as it becomes more and more difficult to find cultures that are completely isolated from the western tonal musical system (Huron, 2008).

Limitations aside, it is important to note that the above-described studies address the question of the potential role of a universal predisposition in driving consonance preferences and do not specifically explore the role of learning. However, a review of the literature on dissonance shows that direct evidence in favour of the role of learning in sensitivity to dissonance has been reported. In particular, an idea that emerges is that learning could influence emotional judgments of dissonance or consonance. In the subsequent sections, we will present converging evidence for this notion across different methodological approaches including those used in neuropsychology, cognitive neuroscience and musicology.

## 2. Influence of learning on emotional judgments to dissonance

The role of learning presents itself as an important consideration regarding the origins of dissonance, specifically since learning processes are not only viewed as important in brain function, but also key players in many aspects of our musical cognition. Learning may generally be described as the process or the experience of gaining knowledge or skill. In musical terms, it may either be incidental, as a result of *exposure* to musical stimuli in the environment, or intentional, as in the case of musicians who acquire sophisticated musical knowledge after years of *training*. Importantly, it appears that both types of learning, via exposure and training, modulate preferences for consonance and aversion to dissonance.

Arguably, one of the earliest sources of direct evidence for the role of exposure in modulating responses to dissonance comes from Meyer (1903). Meyer sought to test the hypothesis that with exposure, music of different cultures becomes more accessible, by '*describing the effect of the music at first hearing and later when it had become more and more familiar*'. To this end, he used quarter tone intervals which are common in Asian music but not present in Western tonal music and demonstrated that while at first, music with quarter-tone tunings was considered unpleasant by Western listeners, the majority of listeners regarded them more pleasant after repeated listening. Corroborating this finding, Valentine (1914) reported similar effects of exposure whereby listeners judged dissonant dyads as becoming more pleasant with increased exposure. The notion, suggested by these results, that the more familiar we become with a particular music the more we develop a positive affect for it, has been further explored by music theorists and psychologists alike (Lundin, 1947). Specifically, Lundin (1947) proposed that the origin of liking judgments to consonance and dissonance is a result of the frequency with which listeners are exposed to the different combinations of sounds and how these sounds are generally received in the social environment. Indeed, the general phenomenon, not specifically related to dissonance processing, whereby exposure drives stimulus preference has been coined 'the mere exposure effect' and has received a great deal of experimental evidence across many psychological domains (Wilson, 1979; Zajonc, 1980). However, in seeking to understand the influence of exposure on emotional responses to dissonance, the study of highly experienced music listeners, who have also carried out more intentional forms of learning, may provide a useful approach; specifically by informing the extent to which the degree of learning may drive both sensitivity and emotional responses to dissonance.

Compelling evidence that what one has been highly exposed to may be very important in the processing of simultaneous sounds has been shown (Moran & Pratt, 1926). Moran and Pratt asked musicians, accustomed to recognising musical intervals by ear, to produce each of a series of intervals by adjusting the frequency of the constituent tones. Results showed that subjects produced intervals that were more in agreement with the intervals in the equally tempered scale (the modern system of tuning used in Western music) than in the just intonation scale (the system of tuning in which frequencies of notes are related by ratios of small whole numbers). This finding suggests that their judgments were based on rules they had internalized from their own musical system to which they are highly attuned (the equal temperament scale) rather than the natural scale that arises from simple rules (the just temperament). Similar influences of exposure are observable in another study in which Western musicians were required to judge perfect fifths of various temperaments (different deviations from the just temperament) (Vos, 1987). While it is important to note that listeners were asked to judge 'acceptability' rather than preference or liking, here again, results revealed that listeners judged the equal temperament intervals, which they have been highly exposed to, as more acceptable than the just temperament intervals, which is less common in modern music. More recent evidence of the role of training as an important determinant of dissonance processing, comes from McDermott et al (2010), who showed that consonance preferences correlated with the number of years subjects had spent playing a musical instrument.

While subjective measures as used by McDermott et al (2010) provide a rich source of information regarding musical preferences, an additional valuable source comes from the measurement of physiological responses. These responses include changes in the skin's electrical conductivity as a result of sweat gland activity (skin conductance response), changes in the rate at which the heart beats (heart rate response) as well as changes in the activity of two major facial muscle groups associated with smiling and frowning (zygomaticus and corrugator activity, respectively). Importantly, these measures have been shown to be modulated by affective valence, the positive or negative qualities of an emotion, listeners have to music (Davis and Thaut, 1989; Krumhansl, 1997; See Hodges, 2010 for review). For example, elevation of skin conductance has been linked to judgements of unpleasantness (Baumgartner, Esslen, & Jancke, 2006; Nater, Abbruzzese, Krebs & Ehlert, 2006), fearful and happy musical phrases (Khalfa, Peretz, Blondin & Manon, 2002), and unexpected harmonies (Steinbeis, Koelsch, & Sloboda, 2006), while it has been reported that listening to dissonant music is accompanied by a greater decrease of heart rate (Nater et al, 2006; Sammler, Grigutsch, Fritz, & Koelsch, 2007) and increased corrugator activity compared to when listening to consonant music (Roy, Mailhot, Gosselin, Paquette & Peretz, 2008).

Based on its obvious capacity to objectively index responses to musical valence, a study from our group used physiological responses in addition to subjective measures to further test the hypothesis that musical experience modulates responses to dissonance (Dellacherie, Roy, Hugueville, Peretz & Samson, 2011). Listeners were assigned to high and low musical experience groups based on their results in a musical questionnaire (Ehrle, 1998). In accordance with a multi-dimensional definition of musicianship, the musical experience questionnaire comprised a *listening subscale* that included items related to their music listening habits and level of musical education and a *practice subscale*, which evaluated amount of regular music practice. All high experience participants, except one who was self taught, had received training in classical music, and none of them reported listening to music genres that are generally high in dissonance (e.g. contemporary music or free jazz). Participants were presented with consonant and dissonant versions of classical music excerpts while skin conductance, heart rate and facial muscle activity were simultaneously recorded. In the first instance, the listeners' subjective reports were shown to replicate not only the general finding that dissonant chords are considered more unpleasant than consonant ones, but also that this difference is influenced by musical experience, with high experience musicians rating dissonant chords as more unpleasant than low experience participants. More importantly, however, differences between high and low musical experience participants was further supported by their measured skin conductance and facial muscle responses. Specifically, the skin conductance response of high but not of low experience listeners showed a late increase in response to dissonant excerpts. Similarly, with regard to the facial muscle responses, high experience groups were shown to produce higher zygomatic responses to dissonant music than consonant music while low experience listeners did not show such effects. Interestingly, while all listeners showed evidence of some sensitivity to dissonance in an early time window, more experienced listeners differed from less experienced ones in a later time window. We took these findings to suggest that musicians carry out further processing of dissonant stimuli than less experienced listeners, potentially at a more conscious level, due to their musical training.

Similarly, numerous electrophysiological studies also provide evidence of differences between musicians and non-musicians in the processing of dissonant stimuli (Brattico et al, 2009; Minati et al, 2009; Regnault, Bigand & Besson, 2001; Schoen, Regnault, Ystad, & Besson, 2005). Regnault and colleagues (2001) showed that the modulation of sensory dissonance of a final chord in a sequence elicited a response in the time window from 300 to 800ms that was greater in musicians than non-musicians. However, the musicians also showed the presence of an early change in the auditory N1 component (a negative going evoked potential that peaks at approximately 100ms after sound onset), that was absent in non musicians, suggesting that musicians may not only carry out further processing of dissonance at a conscious level, but might also have a shorter latency auditory response to dissonance. Schoen et al (2005) would also show a difference in the latency of dissonance processing in musicians and non musicians whereby the evoked potentials of musicians would discriminate intervals judged as pleasant and unpleasant in a 100 to 200ms latency band, while non musicians would only show such evoked potential differences later in a 200 to 300ms band. Finally, Brattico et al (2009) and Minati et al (2009) would show that while responses to dissonance may be found in musicians and non-musicians at a similar latency in some experimental paradigms (in the case of Brattico et al (2009), during an oddball paradigm and in the case of Minati et al (2009), during the presentation of single chords), such responses may be either larger in musicians than in non-musicians (Brattico et al, 2009) or just one part of a larger response, not all of which non-musicians show (Minati et al, 2009). Specifically, in response to dissonant chords, Minati et al (2009) would show no difference between musicians and non-musicians in an early P1 response (a positive going evoked potential peaking at approximately 50ms after sound onset) but a later difference whereby musicians but not non musicians would show an N2 response (the negative going potential peaking between 200 and 350ms after sound onset). Using magnetoencephalography to measure the change-related mismatch negativity response (MMNm) in musicians and non musicians to dissonant, mistuned and minor chords, all in the context of major chords, Brattico et al (2009) demonstrated that while there was no difference between musicians and non musicians in response to minor chords (which relative to mistuned and dissonant chords are frequently encountered in music), the MMNm was stronger in musicians than in non musicians in response to dissonant and mistuned chords. Further, providing direct support for the role of musical training, they showed a correlation between the strength of the MMNm observed in an individual and the length of musical training they had undergone.

Taken together, these studies showing modulation of psychophysiological responses to dissonance as a function both of mere exposure and training provide compelling evidence that learning may play a critical role in responses to dissonance.

Importantly, these lines of evidence from subjective, physiological and electrophysiological measures converge with neuroanatomical studies which implicate the areas involved in memory in the processing of dissonance.

## 3. Overlap between the neural substrates underlying the emotional processing of dissonance and memory processes

Ever since seminal work associating their dysfunction with emotional impairment, the limbic (e.g. hippocampus, amygdala) and paralimbic (orbitofrontal cortex, parahippocampal gyrus, temporal poles) areas are the brain regions most commonly associated with emotion processing. A first piece of evidence that limbic areas are also relevant for music-induced emotion came from Blood and colleagues (Blood, Zatorre, Bermudez, & Evans, 1999) who used Positon Emission Tomography (PET) to examine the cerebral correlates of affective and perceptual responses to musical dissonance. Systematically increasing the degree to which a novel melody was made to sound dissonant by varying the harmonic structure of the chords accompanying it, Blood and colleagues (1999) revealed changes in the cerebral blood flow of the right parahippocampal gyrus and precuneus regions as a function of increasing dissonance, while increasing consonance was shown to elicit changes in bilateral orbitofrontal, medial subcallosal cingulate and right frontal polar cortex.

The authors noted that while the orbitofrontal cortex, the subcallosal cingulate and the fronto-polar regions are often taken to be involved in emotional processing, the parahippocampal gyrus, which derives its name from its proximity to the hippocampal gyrus, is more generally associated with learning and memory processes. Both the hippocampus and parahippocampal gyrus are known to be critical in memory functions (Milner, 1972) and the additional role of the latter in processing dissonance was confirmed by an fMRI study reported a few years later (Koelsch et al, 2006). In this study, in which participants were presented with joyful instrumental musical excerpts and their dissonant versions in order to examine the brain responses that change as a function of dissonance, results revealed, as in Blood et al (1999), increases in activation of the parahippocampal gyrus alongside other areas such as the temporal poles, amygdala and hippocampus.

Functional neuroimaging studies are useful in telling us what areas of the brain are associated with a particular function, however, in certain cases, perhaps even more informative are neuropsychological studies, based on the investigation of brain-damaged patients, which can tell us whether a given brain area is essential for a particular process. This sort of approach is especially useful when numerous areas are shown to be involved with a given brain function but knowledge of specificity is sought. This was the approach taken by Gosselin et al (2006) to further test the specific role of the parahippocampal gyrus in dissonance processing. Two groups of patients with anteromedial temporal lobe lesion (one group with a significant lesion of the parahippocampal cortex, an area encompassing both the posterior parahippocampal gyrus and the medial portion of the fusiform gyrus, and another with participants whose parahippocampal cortex was largely spared) were tested alongside a control healthy group with no lesions. The authors predicted that if the parahippocampal cortex is essential for dissonance processing, then those with this area lesioned would be impaired at making dissonance judgments. Indeed, results showed that parahippocampal cortex lesioned patients judged the dissonant stimuli to be significantly more pleasant than both normal controls and the parahippocampal cortex preserved group. A significant correlation between the anatomical measurement of parahippocampal cortex and individual dissonance ratings in the absence of any other significant correlations was also taken as further evidence of the specific role of the parahippocampal cortex. Finally, the selectivity of the parahippocampal cortex to dissonance processing relative to other types of processing was demonstrated by the fact that judgments of happy and sad music were preserved in parahippocampal cortex lesioned patients.

It is important to note that while auditory areas are necessarily activated in response to dissonance and indeed have been linked to its perceptual processing (Fishman et al., 2001; Peretz, Blood, Penhune & Zatorre, 2001), these areas have not been shown to be associated with the emotional processing of dissonance (Blood et al, 1991). What is striking is the fact that areas involved in the emotional judgments of dissonance overlap with those involved in memory processes: an interesting finding which complements the evidence of a role of learning processes in emotional responses to dissonance.

## 4. Musical consonance: The effect of context and culture

While the current review focuses on literature investigating responses to sensory consonance and dissonance and highlights evidence that these responses are likely modulated by exposure and learning, consideration of what happens in a musical context is clearly also important. Indeed the musicologist Cazden (1980) questioned the relevance of the study of listeners' responses to single chords or dyads if the greater aim is to understand these responses with respect to real music. With regard to what might bring about differences in the perception of such isolated sounds in a musical context, he emphasised the importance of expectations. He would argue that consonance or dissonance cannot exist without the *'framework for normative expectations'* adding that responses to consonance and dissonances will be distorted *'should the apparent resolution tendencies and outcomes be thwarted consistently'*. Importantly, he suggests that the expectations listeners have, based on what they have internalized over a lifetime of listening, is what explains differences in the perception of music across cultures, and why Western listeners, for instance, will struggle to appreciate the gamelan music of Bali. In support of this emphasis on musical context is the evidence that perception of a given interval is dependent on the musical style within which the interval is found. Indeed, it has been shown that tones combined at simple ratios, which should be therefore considered consonant, can be judged as dissonant when occurring in an unexpected musical context (Dowling & Harwood, 1986).

Critically, the importance of exposure and learning on consonance and dissonance judgments in a more musical context can be seen in the developmental trajectory of music listening in children. Indeed it interesting to note that, while, as previously described, young infants show preference for consonance very early (suggesting if not innate tendencies then, at least, very rapid learning), they must reach a certain age before they develop a robust knowledge of harmony, and specifically the ability to judge the appropriateness of a progression of chords either on its own or as accompaniment to a melody (Belaiew Exemplarsky, 1926; Bentley, 1966; Bridges, 1965; Imberty, 1969; Schellenberg, Bigand, Poulin, Garnier & Stevens, 2005; Valentine, 1913; Zimmerman, 1971). Both Minkenberg (1991) and Zenatti (1993), for instance, showed significant changes in this ability from the age of 5 to 9. Specifically, Zenatti (1993) presented children with pairs of musical stimuli and asking which they preferred, demonstrated that while at the age of 5 there was no clear preference for consonant musical stimuli, by the age of 9 there was. It is worth noting that since then other studies have shown evidence of implicit knowledge of western music harmony in 5 and 6 year olds using a priming paradigm (Schellenberg et al, 2005) and EEG (Koelsch, Grossman, Gunter, Hahne, Schroeger & Friederici, 2003). It is possible that implicit forms of knowledge may precede explicit forms resulting in the differences seen here. Nevertheless, taken together these findings may be taken to suggest that only by the age of 5 are children at least basically enculturated in their musical system. Conversely, they are in line with the observation that children's appreciation of music from other cultures begins to drop from about the age of 5 (Colwell & Richardson, 2002).

## 5. Implications: Culture, familiarity and a historical perspective

The evidence that exposure and learning affects consonance and dissonance judgments has important implications for our understanding of how and why music evolved as it did over time. It is interesting to note that while only perfect intervals (fourths and fifths) were accepted as consonances in compositions in the Middle Ages and early Renaissance, intervals higher in the harmonic series and therefore more dissonant (thirds and sixths) were increasingly used in the 15th and 16th centuries, and today it is common to see highly dissonant intervals in contemporary music. Such a trend speaks to a notion of tolerance to dissonance growing with cultural exposure. Indeed as pointed out by Schoenberg (1911), increasingly higher members of the harmonic series may have gradually become recognized as consonant as they became more familiar.

The notion that the adoption of increasingly more dissonant chords in music over time is due to familiarity also ties in with the notion that a listener's interest in music relies on, music's ability to fulfil and thwart their expectations (Meyer, 1956). Indeed, increasing use of dissonances may have been driven by the fact that following repeated exposure to the same harmonic materials, listeners' expectations during music listening became so accurate that composers had to introduce more sophisticated harmonic materials to keep them interested. An interesting way of testing this notion would be to examine the rate of change in the use of musical dissonance over time. One prediction is that rate of change in the use of dissonance will correlate with the degree of exposure people have to music over time.

It is important to note, however, that while listeners' tastes have likely evolved such that they are able to tolerate greater use of dissonance in music, such changes may not always result in a greater liking. In other words, there might be a limit to the extent to which dissonant materials will be embraced and accepted by listeners. Indeed given the amount of exposure to music the average listener has today, which is considerable with the ubiquity of personal musical devices, one might expect to see a speeding up rather than slowing down of the use of harmonic complexity in music (Parncutt & Hair, 2011). At any rate, an interesting implication of learning influencing consonance and dissonance judgments is that not only do listeners today have the capacity to internalise the rules guiding polyphony of previous times, but also that this learning may in turn have the capacity to modulate their emotional response to it.

Finally, while the current review provides evidence that consonance judgments change with increasing musical experience, an interesting question which presents itself is the extent to which, regardless of musical experience, an individuals' familiarity with a particular musical piece will affect their response to it. Meyer (1903) and Valentine's (1914) studies showing increased liking of quarter tone intervals and dissonant dyads with increasing presentation, as well as work from others emphasising the importance of exposure on liking judgments (Cazden, 1980; Lundin, 1947; Zajonc, 1980), suggest that consonance judgments can and do change with familiarity with a stimulus. However, the question of familiarity influencing perceptions of consonance and dissonance in specific musical works remains an empirical question, the answer to which could inform our understanding of how listeners experience consonance and dissonance in everyday life.

## Conclusion

Following a brief overview of the literature assessing the extent to which preferences for consonance may be innate, the current review presented the growing evidence for an important role of exposure and learning mechanisms in dissonance processing. In addition to early behavioural studies showing that exposure increases aesthetic preferences by modulating affective responses, it highlights converging evidence from physiological and electrophysiological studies showing that musicians are more sensitive to dissonance than non-musicians. It also highlights neuroimaging and neuropsychological studies showing that areas normally implicated in memory processes are also highly involved in the judgment of dissonance. Critically, in doing so it shows the relevance of complementary methodologies from neuropsychology, affective neuroscience and musicology in addressing an age-old question. Finally, the current review suggests that a parsimonious theory of dissonance should incorporate learning and memory processes, and provides a framework for considering the changes in the use of dissonance in music over the centuries.

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[i] Around the same time, in 1890, Lissauer would make a distinction between two types of visual 'asymbolia' (later coined agnosia by Freud (1891)): an apperceptive one, whereby early visual processing of a stimulus is disrupted resulting in a failure to generate a full representation and associative asymbolia, referring to a failure to recognize and therefore name the stimulus despite having generated a representation of it. 100 years later, Vignolo (1982) would carry the notion to the auditory domain distinguishing between apperceptive and associative auditory agnosias.

## Biographies

**Diana Omigie** is a researcher at the Max Planck Institute for Empirical Aesthetics in Frankfurt am Main, Germany. Prior to her current position, she carried out a postdoctoral fellowship based both at the University of Lille and the Brain and Spine Institute in Paris, France. After an undergraduate degree in Neuroscience at University College London, she completed a Ph.D in Psychology at Goldsmiths, University of London in 2012. Under the supervision of Dr Lauren Stewart, her thesis examined the cognitive and neural bases of congenital amusia using behavioural and electrophysiological methodologies. Her broad research interests lie in the role of learning and expectation processes in music cognition as well as the neurobiological basis of music-induced emotions and aesthetic judgments.

**Delphine Dellacherie** is a cognitive neuropsychologist and an associate professor of Psychology at the University of Lille in France. After post graduate studies in Philosophy at the University of Paris-Sorbonne, she completed a Ph.D in Psychology at the University of Lille in 2009. Her thesis, carried out under the supervision of Professor Severine Samson, examined the cerebral correlates of musical emotion using a multidisciplinary method combining behavioural neuropsychology and neurophysiology. She is currently teaching Neuropsychology and holds a clinical position in Neuropediatry and Neurosurgery at Lille hospital. Her research focuses on the neurobiological basis of emotion and memory in auditory and musical domains using fundamental and applied research.

**Séverine Samson** is a cognitive neuropsychologist and a full professor of Psychology at the University of Lille in France. After her Ph.D. in Experimental psychology at the McGill University (Montreal) in 1989, she took on a faculty position at University of Lille and was nominated in 2008 and in 2014 as senior member at Institut Universitaire de France. Her research focuses on perception, memory and emotion in musical and non-musical domains using methods taken from Psychophysics, Cognitive psychology and Neuroimagery. She is currently involved in several international and national projects. Her work is applied in Neuropsychology and rehabilitation.