# Chills in music: An integrative review[*]

Rémi de Fleurian[a] Marcus T. Pearce[a,b]

[a] *Cognitive Science Research Group, Queen Mary University of London*
[b] *Center for Music in the Brain, Aarhus University & Royal Academy of Music*

**Abstract**

Chills are a psychophysiological response which can be experienced when listening to music. They have been of particular interest in scientific research on music because of their association with emotion and pleasure. With the literature almost doubling in size since the last review on the subject, a comprehensive survey is needed to provide a solid basis for future research. In this article, we explore the context behind current research on chills, discuss how they relate to emotional and aesthetic responses, assess current empirical measures and paradigms, summarise their physiological and neural correlates, categorise their possible stimulus-driven elicitors, examine how they are affected by individual differences, and evaluate theories about their potential evolutionary causes. We conclude by providing a set of recommendations for future research, and include a dataset listing pieces of music reported to elicit chills in the reviewed literature.

*Keywords*: chills; piloerection; music; emotion; aesthetics; pleasure; arousal; reward; personality; being moved; expectation; evolutionary mechanisms

# Contents



[*]Preprint submitted for peer review.

# 1 Introduction

Chills are a psychophysiological response which can be elicited by music listening. Frequently cited papers describe chills as "a spreading gooseflesh, hair-on-end feeling that is common on the back of the neck and head and often moves down the spine" (Panksepp, 1995, p. 173), "a particularly intense, euphoric response to music [frequently accompanied] by an autonomic or psychophysiological component" (Blood & Zatorre, 2001, p. 11818), "intense emotional experiences involving sensations such as goose bumps or shivers down the spine" (Koelsch, 2010, p. 131), or "a pleasant tingling feeling associated with the flexing of hair follicles, resulting in gooseflesh (technically called piloerection) accompanied by a cold sensation, and sometimes producing a shiver" (Huron & Margulis, 2010, p. 591).

While superficially similar, these definitions are symptomatic of the current state of the literature on chills experienced in response to music listening, in the sense that it is difficult to reconcile diverging opinions and empirical findings on what chills represent. From these definitions alone, crucial questions about chills arise. How are chills best defined? Is piloerection a required component or an occasional consequence of chills? Are chills pleasant? Should they be considered as an emotional response? Why do they occur? The fact that such questions remain at least partially unanswered is reflective of the fact that, along with growth in academic interest for chills, the increasing diversity of experimental findings can be confusing, sometimes leading to conflicting views. This motivates the need for a comprehensive integrative review as provided here.

Chills are often mentioned in the literature on music and emotion, but at the time of writing, there are only two short reviews dedicated to chills (Grewe et al., 2009b; L. Harrison & Loui, 2014), one philosophical essay about chills and musical aesthetics (Levinson, 2006), two book chapters discussing chills within the context of musical expectation (Huron & Margulis, 2010) and of the evolutionary basis of music (Altenmüller et al., 2013), and book chapters on music and emotion which contain sections on chills (e.g., Corrigall & Schellenberg, 2013, 2015; Hodges, 2016; Hunter & Schellenberg, 2010; Juslin, 2019; McDermott, 2012; Vuust & Kringelbach, 2010). These contributions are informative and useful, but they are not comprehensive. Moreover, the literature has almost doubled in size since the review by L. Harrison and Loui (2014)—in this article, we review 80 contributions about chills dated 2014 or prior, and 66 contributions dated 2015 or later (see Figure 1 for yearly publication count). The purpose of this article is therefore to review exhaustively 40 years of academic research on chills experienced in response to music listening, from the first mentions of the phenomenon by Goldstein (1980) and Panzarella (1980), through important,

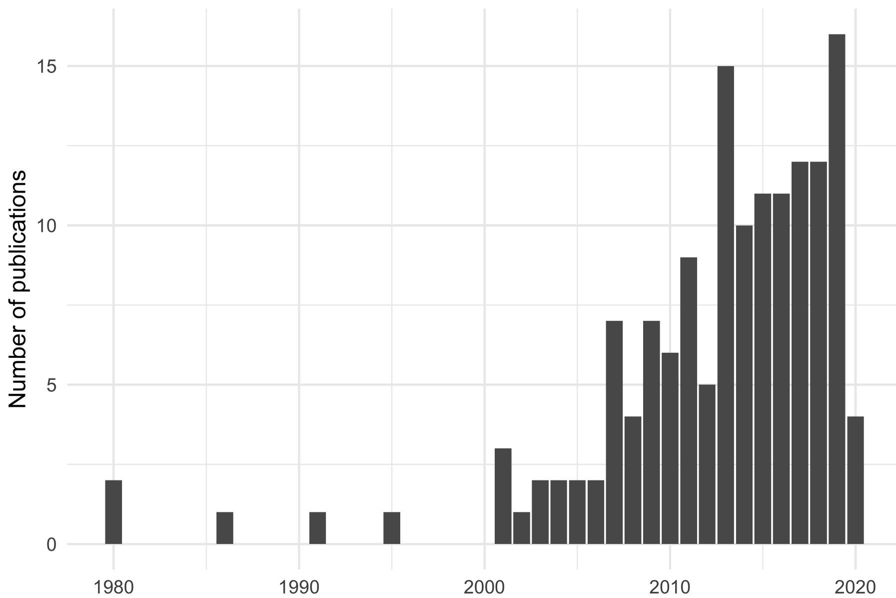


Figure 1: Yearly publication count for research on the topic of chills reviewed in this article.

early work by Sloboda (1991), Panksepp (1995), and Blood and Zatorre (2001, which remains to this date the most cited paper on chills and music), to more recent contributions up to early 2020.

The article is structured as follows (see Figure 2 for a visualisation). Sections 2, 3, and 4 consider the wider context within which empirical and theoretical research on chills has been conducted. We begin in Section 2 by considering terminological issues, the phenomenological and physiological nature of chills, their prevalence and frequency, and their relationship with other psychological processes. In Section 3, we expand on the nature of the relationship between chills, pleasure, and emotional and aesthetic experience, before assessing subjective and objective ways of measuring chills, as well as experimental paradigms used in research on chills in Section 4. In the subsequent sections of the paper, we review the empirical literature on the biological basis of chills, considering associations between chills, arousal, and physiological responses (Section 5), and neural correlates of chills in the basal ganglia and other brain structures (Section 6). We then turn to theoretical considerations regarding the causes of chills. We review the empirical literature to identify the stimulus-driven causes of chills and categorise them into acoustic, musical, and emotional elicitors (Section 7), examine empirical effects of individual and personality differences on the occurrence of chills (Section 8), and critically evaluate the degree of support provided by the reviewed evidence for current psychological theories of chills (Section 9). We conclude by providing a set of recommendations for future

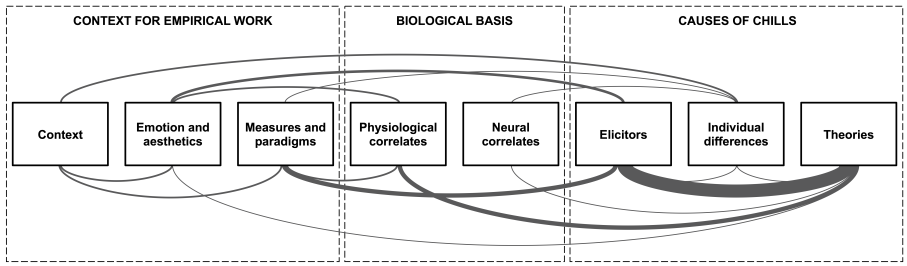


Figure 2: Visualisation of the structure of this article. Rectangular boxes correspond to sections, presented in order left to right, which are grouped into three overarching themes. The number of cross-references between sections is proportional to line width and ranges from 1 (e.g., between Neural correlates and Individual differences) to 15 (between Elicitors and Theories).

research, and include a dataset listing pieces of music reported to elicit chills in the reviewed literature (Section 10).

# 2 Context

A significant amount of research has focused on identifying exactly what chills are, but there remains uncertainty about many of their defining aspects. In this section, we review the terminology associated with chills, their physiological and phenomenological nature, their prevalence and frequency, and their relationship with other psychological processes, including emotional and aesthetic responses to music.

## 2.1 Terminology

Besides definitions of chills, an initial source of confusion is the broad range of terms used to refer to the phenomenon. Terms such as musical chills, aesthetic chills, art-elicited chills, shivers, shivers down the spine, psychogenic shivering, thrills, frisson, goosebumps, gooseflesh, goose pimples, piloerection, emotional piloerection, hair standing on end, and skin orgasm, have been used interchangeably over the years, and there is no explicit consensus as to which option should be preferred. L. Harrison and Loui (2014) recommended the use of *frisson*, a term first used in the context of research on chills by Huron (2006) and Levinson (2006), which has the advantage of providing a relatively nonspecific way to describe an emotional response with a physiological component, while avoiding the burden of cultural associations present in other terms. While this is a sound recommendation, the term *frisson* is sparsely used in the literature. We would argue that the need for a unified term of reference outweighs considerations about the colloquial use of the term, and therefore recommend the use of *chills*[1], which has quite clearly become the most prevalent term in the recent literature. In this article, we use *chills* (for the psychophysiological response) and *piloerection* (for goosebumps specifically) throughout, except when referring to specific findings from authors who used several terms in a single publication.

## 2.2 Phenomenological and physiological nature

Regardless of the terminology used, it is important to have a clear and consistent conception of the nature of chills. This would ensure that participants in research on chills provide responses about the same psychophysiological phenomenon. Failing to do so might lead to inconsistent empirical findings, making interpretation problematic and creating difficulties in relating empirical results between studies. However, identifying a clear and consistent phenomenological description of chills is not straightforward in the existing literature. Goldstein (1980) provided a thorough starting point through a series of unstructured and structured questionnaires, in which several groups of participants were asked to describe their experience of chills. The results characterised chills as a transient, pleasurable response associated with sudden changes in mood or emotion, commonly experienced by a large proportion of the population, and originating primarily in the upper spine or back of the neck, with other common points of origin being shoulders, lower spine, and scalp. Intense occurrences of chills were described as longer in duration, and radiating to other body areas (most commonly the scalp, arms, shoulders, spine, and face). There are further, varying reports of the physiological location from which chills in response to music originate. The back (or spine), head (or scalp, face, or neck), and arms are the most commonly reported points of origin (Craig, 2005; Goldstein, 1980; Panksepp, 1995; Wassiliwizky et al., 2015), with occasional mentions of hands or fingers (Craig, 2005), as well as legs (Wassiliwizky et al., 2015).

Interestingly, Craig (2005) made the distinction between points of origin for shivers or tingling (listed above) and piloerection, which was most often reported to begin on the arms, back of the neck, or legs. This raises the important question of whether piloerection should be considered as an integral component of chills or not. Again, opinions differ. While some definitions of chills suggest that piloerection is required (Huron & Margulis, 2010; Panksepp, 1995), most do not (e.g., Blood & Zatorre, 2001; Goldstein, 1980), and empirical findings support the latter view. In self-reports, piloerection is often reported to happen less often than chills (Gabrielsson, 2011; Silvia & Nusbaum, 2011; Sloboda, 1991). In experimental settings, piloerection was only observed in 57% (Craig, 2005), 40% (Benedek & Kaernbach, 2011), 43.1% (Sumpf et al., 2015), and 40.7% (Wassiliwizky, Koelsch, et al., 2017) of participants who reported chills. Seemingly, not all chills involve piloerection (Craig, 2005), although most

[1]Following common usage in the literature, we use the word "chills" as a plural-only, non-countable noun, like clothes or groceries. We feel this is consistent with the difficulty of identifying exactly what would constitute an individual chill (or a definite number of chills) and find it more natural to refer, for example, to an episode of chills.

(Benedek & Kaernbach, 2011) or all (Craig, 2005) occurrences of piloerection were found to happen during experiences of chills. It is therefore likely that chills, as reported by participants, do not always involve piloerection, although it is possible that experienced chills might require an intensity threshold to be reached before piloerection can be observed (Sumpf et al., 2015), or that current piloerection detection methods are simply not accurate enough (for an overview of available methods, see Subsection 4.2). While relying on self-reported or observed piloerection to study chills is tempting, due to the objectivity it provides, it seems more appropriate at this stage to combine such an approach with self-reports of chills (e.g., Wassiliwizky, Koelsch, et al., 2017), in order to avoid biasing research away from what people actually experience as chills (Maruskin et al., 2012).

## 2.3 Prevalence and frequency

While 79% of the 249 participants who completed Goldstein's (1980) questionnaires reported having experienced chills in the past, additional figures about the prevalence of the ability to experience chills are available in the literature: 90% of a sample of 83 respondents for experiencing shivers down the spine at least once in the past five years (Sloboda, 1991, also reporting 62% for goose pimples and 31% for trembling), over 80% of 186 respondents for experiencing shivers down the spine or goose pimples at least rarely over the past five years (Mlejnek, 2013), or 86% of 828 respondents for experiencing chills with some regularity (Panksepp, 1995). In a survey of 196 people by Nusbaum and Silvia (2011), 8% of respondents never or rarely experienced chills, and in a survey of 188 people by Silvia and Nusbaum (2011), 11.2%, 9.6%, and 23.5% never or rarely experienced chills down the spine, goosebumps, and feeling hair standing on end, respectively, although it is worth keeping in mind that for the latter, only half of the reports were about experiences when listening to music. There are further figures available in the literature, but when looking at prevalence, it makes sense to consider only results from surveys of a reasonably representative sample of the population, since participants in lab experiments have most often been recruited for their ability to experience chills, and might also not have been able to experience chills under experimental conditions for a variety of reasons. Limitations remain, due to the fact that people interested in taking surveys about reactions to music might not be fully representative of the population, but from these results, it is reasonable to assume that 90% is an upper limit for the proportion of the population that has the ability to experience chills when listening to music. Interestingly, when providing free reports of their strongest, most intense experience of music, respondents spontaneously included chills or shivers in 10% of their reports, and piloerection or gooseflesh in 5% of their reports (Gabrielsson, 2011).

In terms of frequency, those who experience chills seem to do so quite regularly. Chills are reported as the most frequent (Sloboda, 1991) or second most frequent physical response to music, behind tears (Gabrielsson, 2011; Scherer et al., 2001), and happen with some regularity for most people (Panksepp, 1995), ranging from every week to every few months (Bannister, 2020a; Goldstein, 1980). For instance, during a week of experience sampling, 81% of respondents reported having at least one experience of chills, and reported chills in 14% of the occurrences of listening to music (Nusbaum et al., 2014).

## 2.4 Relation to other psychological processes

Another step in better understanding chills is to examine the role they play in emotional and aesthetic responses to music, with studies in which such responses are classified using content analysis, factor analysis, or principal component analysis. Panzarella (1980) found that chills belong to one of the four major dimensions which can describe intense, joyous experiences of listening to music or looking at visual art. This dimension, called *motor-sensory ecstasy*, was found to be mostly associated with the climactic stage of an aesthetic experience. Scherer et al. (2001) coded qualitative reports of the last time respondents were emotionally affected by a piece of music, and assigned chills and piloerection to one of five major emotion components, called *physiological symptoms*. Gabrielsson and Wik (2003), as a part of their work on identifying the components and causes of strong experiences related to music (Gabrielsson, 2001), found that in descriptions of the strongest, most intense experiences of music reported by almost 900 participants, chills and piloerection were best coded and classified as *physiological reactions*, a sub-component of *physical reactions and behaviours*. Zentner et al. (2008), in a series of studies aimed at identifying and validating a taxonomy of musically induced emotions for the development of the Geneva Emotional Music Scale, retained chills as one of 40 items present in a second-order model of musical emotions. Chills were found to belong to one of nine first-order factors, *transcendence*, which itself belongs to one of three second-order factors, *sublimity*. Silvia and Nusbaum (2011) found that out of twelve unusual aesthetic states, the three states related to chills (chills down the spine, hair standing on end, goosebumps) made up one of three factors, simply called *chills*. The three factors (chills, touched, absorption) all loaded strongly on a single higher-order factor for *aesthetic experience*. In developing the Barcelona Musical Reward Questionnaire, Mas-Herrero et al. (2013) included an item about chills as one of twenty items that best capture individual differences in how people experience reward associated with music. This item loaded highly on one of five factors, named *emotional evocation*. Bannister (2020a) coded a large number of reports of how surveyed participants felt during the experience of chills, and identified *emotions and feelings* and *physical reactions* as the two themes accounting for most responses. Finally, Cotter et al. (2018) used chills as an item in a twenty-four-item questionnaire about feeling like crying in response to music. The two resulting latent classes were named *awe* and *sad*, with higher levels of experiencing chills for the former than for the latter—a finding that was replicated in a subsequent study (Cotter et al., 2019).

Two contributions using similar approaches deserve particular consideration, due to their exclusive focus on the experience of chills. Maruskin et al. (2012) put forward a convincing argument that chills might consist of a set of distinct phenomena with different psychological and biological bases. This motivated an extensive body of work in which a wide range of self-reports of the experience of chills associated with emotionally significant events were analysed in order to gain a better understanding of chills as a psychological construct. It was found that chills are best understood as comprising four conceptually distinct sensations: goosebumps, tingling (grouped together as a higher order factor, *goosetingles*, associated with positive affective states), coldness, and shivers (grouped together as *coldshivers*, associated with negative affective states). Similarly, Bannister (2019), using a quantitative approach, investigated whether chills should be considered as a single psychological construct, reflective of intense pleasure and emotion, or as an umbrella term for distinct experiences. Analysis of responses to questionnaire items revealed that chills can be conceptualised as comprising three categories: *warm chills* (associated with positively valenced feelings and physical responses), *cold chills* (associated with negatively valenced feelings and physical responses), and *moving chills* (associated with more ambiguous responses, such as tears, feeling a lump in the throat, affection, or tenderness, among others). Although it is tempting to draw parallels between the categories identified by Maruskin et al. (2012) and Bannister (2019), they are not directly comparable because they were derived from responses to emotionally significant events in one case, and aesthetic stimuli in the other. Regardless, these considerations are of particular importance, because if chills are indeed a collection of phenomenologically and psychologically distinct experiences, failing to distinguish between them might lead to null, conflicting, or misleading results (Bannister, 2019; Maruskin et al., 2012). Note, however, that the vast majority of research on chills continues to treat them as a single construct.

It is worth noting that several studies reviewed in this section and in the rest of this article do not exclusively pertain to reactions to music. These studies were included if they counted music as one of several investigated modalities, or if they reported results relevant to research on chills in music. For instance, chills are known to occur in response to visual stimuli (Bannister, 2019; Goldstein, 1980; Grewe et al., 2011; Maruskin et al., 2012; Panzarella, 1980; Silvia & Nusbaum, 2011; Sumpf et al., 2015; Wassiliwizky, Jacobsen, et al., 2017), and also to text, poetry, film audio, sounds (human, animal, natural, and technical), speech, beauty in nature, touch, smell, taste, memories, and virtual reality environments, among others (Benedek & Kaernbach, 2011; Goldstein, 1980; Grewe et al., 2011; Konečni et al., 2007; Quesnel & Riecke, 2018; Schurtz et al., 2012; Wassiliwizky, Koelsch, et al., 2017). In cases where occurrences of chills were compared across modalities, there is no consensus as to whether music should be considered the most potent elicitor (Goldstein, 1980; Sumpf et al., 2015) or not (Bannister, 2019; Benedek & Kaernbach, 2011; Grewe et al., 2011; Schurtz et al., 2012). Two of these studies set out to answer that question explicitly through surveys (Goldstein, 1980; Schurtz et al., 2012), while the other analyses of this effect simply compared occurrences of chills across the specific sets of stimuli used in each study, making it difficult to assess how generalisable these results are.

### 2.5 Summary

Most of the empirical work reviewed so far relies on the analysis of self-reports, and on a certain degree of subjective input from the researchers when it comes to interpreting and naming overarching categories and underlying factors. Taken together, however, these results suggest that, while chills are a complex psychological construct, most of the population experiences them with some regularity when listening to music. They might comprise several psychologically distinct phenomena, are thought to be related to emotional and aesthetic experiences, and to involve a physiological component, which most often originates in the back, head, or arms, and can include piloerection. Establishing a clear and consistent conceptual understanding of what exactly is being studied when researching chills is a critical issue that deserves further attention, and it is hoped that this article makes a contribution towards this objective.

## 3 Emotion and aesthetics

As discussed in the previous section, chills have been fairly consistently classified as components of emotional or aesthetic experiences. However, there is also considerable discussion about what constitutes such experiences, and therefore their specific relationship with chills deserves clarification. In this section, we review how chills are associated with emotional responses, pleasure, and aesthetic responses.

### 3.1 Emotional response

Chills are often discussed in book chapters on music and emotion, either as a physiological response which can accompany intense musical emotions (Juslin, 2016), or as a strong, specific emotional reaction to music (Eerola, 2018; Hunter & Schellenberg, 2010). To disentangle these interpretations, it is useful to refer to definitions of musical emotions. Chills show some of the qualities of emotional states, as defined by Juslin et al. (2010), because they can involve a *subjective experience*, observed in self-reports of emotional reactions to music (see Subsection 2.4), and because they have been shown to involve *physiological arousal*, both in terms of measured physiological responses and self-reported arousal (see Section 5). However, chills do not exhibit other characteristic components of emotional states, such as *motor expression* or *action tendency* (Juslin et al., 2010; Scherer, 2009), and they can be associated with positive or negative valence (e.g., Bannister, 2019; Maruskin et al., 2012). These considerations suggest that, instead of being considered as an emotion category or emotional state per se, chills are best understood as a psychophysiological response which can form part of a range of emotional states (Grewe et al., 2011; Juslin, 2019).

## 3.2 Pleasure

In this article, we make a distinction between pleasure experienced while listening to music and positively valenced music-evoked emotion (see E. Schubert, 2013). It is perfectly possible, for example, to experience sadness while listening to a piece of music but also to find that experience pleasurable. Most studies of chills have treated them as a pleasurable response to music. Interestingly, this notion permeated the early literature on chills despite limited evidence at the time that chills were indeed associated with pleasure (Blood & Zatorre, 2001; Goldstein, 1980). Since then, research has confirmed that such an association exists, as shown by an analysis of qualitative reports in an extensive survey (Bannister, 2020a), by significant increases in pleasure occurring immediately prior to the onset of chills and peak pleasure coinciding with chills (Salimpoor et al., 2009), by a joint increase in pleasure and occurrence of chills when watching video clips preceded by a meaningful statement as opposed to an incoherent statement (Schoeller, Eskinazi, et al., 2018; Schoeller & Perlovsky, 2016), by chills playing a role in driving music preference (Schäfer & Sedlmeier, 2010, 2011), and more generally, by a documented association between chills and self-reports of increased subjective pleasure when listening to music (Grewe et al., 2011; Grewe et al., 2009a; Grewe et al., 2007; Mori & Iwanaga, 2014, 2015, 2017; Salimpoor et al., 2011; Salimpoor et al., 2009; Sumpf et al., 2015). Interestingly, displeasurable chills can also be experienced in response to unpleasant sounds (Grewe et al., 2011; Grunkina et al., 2017; Halpern et al., 1986; Klepzig et al., 2020). Given that chills can form a part of unpleasant experiences, it is possible that chills in response to music listening are generally experienced as pleasurable because music listening itself is generally a pleasurable activity (Dubé & Le Bel, 2003).

## 3.3 Aesthetic response

Since chills arising while listening to music are generally experienced as pleasurable, their role in aesthetic responses also deserves clarification (Hodges, 2016). Chills have been referred to as one of several indices of aesthetic experiences of music (E. Schubert et al., 2016; Vuust & Kringelbach, 2010). As noted in Subsection 2.4, previous questionnaires and qualitative reports about aesthetic responses to music have included chills (Panzarella, 1980; Silvia & Nusbaum, 2011). To better understand this relationship, we need a precise definition of the aesthetic appreciation of music. Here, we follow Levinson (2009) in characterising aesthetic appreciation as a positive estimation based on an intrinsically pleasurable experience arising from attention directed to the form and content of a piece of music. Based on the range of psychological components thought to be involved in aesthetic appreciation (see Leder et al., 2004; Leder & Nadal, 2014, for another extensive, multi-component model), it seems unlikely that chills should be considered as an aesthetic experience in and of themselves. Rather, a more promising interpretation would be that chills can contribute to aesthetic experiences, because they constitute a pleasurable response to some musical properties (see Section 7). Indeed, in a philosophical essay about chills, Levinson

(2006) argues that they provide a signal that something significant happened in the music—in other words, a focuser of attention—and in so doing, make a valuable contribution to wholly experiencing a piece of music, through a culmination of cognitive, emotional, physiological, and behavioural responses. According to E. Schubert et al. (2016), this contribution, and that of other subjective experiences evoked by music (or *internal locus* affects), is what motivates people to seek out aesthetic experiences. Many researchers have considered chills to form an optional, rather than a central, component in the aesthetic experience of music (e.g., Brattico et al., 2013; Gabrielsson et al., 2016; Konečni, 2007), and this is a view we share, in light of the reviewed literature.

### 3.4 Summary

The relationship between chills, emotions, and aesthetics is complex. The purpose here is not to provide a comprehensive review of the literature on emotion and aesthetics, but rather to situate chills within well-established frameworks of aesthetic and emotional responses to music, which are widely—though not always universally—accepted. From the evidence reviewed in this section, we conclude that chills are a pleasurable psychophysiological response to music, and a possible, though not essential, component of emotional and aesthetic experiences of music. This makes them unsuitable as the sole indicator of such experiences, but if used in conjunction with self-reports, they provide attractive properties from an experimental point of view, because they are pleasurable, widespread, stable, memorable, discrete, and when accompanied by piloerection, objective and observable (Brattico & Pearce, 2013; Brattico & Varankaitė, 2019; Grewe et al., 2009b; McDermott, 2012; Sloboda, 1991; Vuust & Kringelbach, 2010; Zatorre, 2003).

## 4 Measures and paradigms

Most of the early research on chills focused on the analysis of survey answers. As the need for experimental data grew in order to adequately investigate chills occurring in response to specific stimuli, the methods used in lab or online studies became increasingly diverse. These methods are described in this section, with a focus on self-reports, objective measures of chills, and experimental paradigms, which have dominated the empirical literature on chills.

### 4.1 Self-reports

When listening to music, chills can either be self-reported or observed, and recorded retrospectively or continuously. A popular and convenient way to measure chills is to rely completely on retrospective self-reports about the frequency or intensity of chills (Bannister, 2019; Blood & Zatorre, 2001; Carr & Rickard, 2016; Goodchild et al., 2019; Jaimovich et al., 2013; Juslin et al., 2014; Park et al., 2019; Schäfer & Sedlmeier, 2011; Schoeller, Eskinazi, et al., 2018; Schoeller & Perlovsky, 2016; Seibt et al., 2017; Silvia et al., 2015; Solberg & Dibben, 2019; Strick et al., 2015; Wassiliwizky et al., 2015; Weth et al., 2015), generally collected with a short questionnaire after each trial. This has the advantage of requiring virtually no resources, but is also one of the least informative ways to record chills. As a more detailed approach, continuous self-reports allow researchers to collect data on the specific timing of the onset—and sometimes offset—of chills, with the exception of two studies in which participants were asked to keep a count of experiences of chills on a scratch sheet (Balteș et al., 2011; Balteș & Miu, 2014). In their simplest form, continuous self-reports can be collected by asking participants to raise their finger or hand for the duration of experienced chills (Craig, 2005; Goldstein, 1980; Konečni et al., 2007; Panksepp, 1995). Most commonly, however, participants report chills by pressing on a button (Bannister, 2020b; Beier et al., 2020; Colver & El-Alayli, 2016; Egermann et al., 2011; Ferreri et al., 2019; Grewe et al., 2011; Grewe et al., 2009a; Grewe et al., 2007; Guhn et al., 2007; Laeng et al., 2016; Mas-Herrero et al., 2014; Mori & Iwanaga, 2014, 2015, 2017; Nagel et al., 2008; Rickard, 2004; Sachs et al., 2016; Salimpoor et al., 2011; Salimpoor et al., 2009; T. W. Schubert et al., 2018; Seibt et al., 2018; Starcke et al., 2019; Sutherland et al., 2009; Wassiliwizky, Koelsch, et al., 2017; Zickfeld, Schubert, Seibt, Blomster, et al., 2019), achieved in several studies using *EMuJoy* (Nagel et al., 2007), bespoke software that also allows continuous self-reports of valence and arousal in a two-dimensional interface. In a few cases, an analogue slider (Bannister & Eerola, 2018) or a pressure-sensitive handle (Grunkina et al., 2017; Klepzig et al., 2020) have been used instead of a button to collect continuous ratings of chills intensity, rather than a binary response about the occurrence of chills.

An important methodological consideration in studies that use button presses for chills and collect skin conductance response data is whether the act of pressing a button raises skin conductance response by itself. This has been consistently demonstrated not to be the case (Bannister, 2020b; Colver & El-Alayli, 2016; Grewe et al., 2011; Grewe et al., 2009a; Grewe et al., 2007; Guhn et al., 2007; Mori & Iwanaga, 2014, 2015; Rickard, 2004; Salimpoor et al., 2009). Relatedly, several studies have validated button presses by only including them in the analysis if they are accompanied by an increase in skin conductance response (Bannister, 2020b; Beier et al., 2020; Colver & El-Alayli, 2016; Egermann et al., 2011; Grewe et al., 2007; Mori & Iwanaga, 2014). This approach has the advantage of not exclusively relying on self-reports, but considering the current lack of understanding regarding the exact relationship between chills and skin conductance response (see Subsection 5.1), it might also lead to valid occurrences of chills being discarded.

## 4.2 Objective measures

The ideal way to record chills would consist of an objective and continuous measure. Panksepp and Bernatzky (2002) made a brief reference to an inconclusive attempt at measuring chills using thermal imaging of the skin surface, following a suggestion to use objective measures in an earlier publication (Panksepp, 1995). The authors concluded that directly measuring piloerection might be more appropriate, as previously suggested by Sloboda (1991). This can be done manually, as was the case in a study in which participants placed their arm through a curtain, and observers noted the onset and offset of piloerection (Craig, 2005), or automatically, using devices which can monitor piloerection.

The most notable example of such devices is the *Goosecam* (Benedek et al., 2010), an optical device which can be roughly described as a camera embedded in a box that blocks external light, recording the skin of the forearm—or lower leg in some later studies—from a close distance. LED lights shine on the skin at an angle from within the box, allowing goosebumps to cast a shadow on the skin. Images are then processed with a MATLAB toolbox using a discrete Fourier transform to provide a continuous measure of piloerection. A piloerection event occurs if the computed value exceeds an arbitrarily set threshold—usually defined in terms of the number of standard deviations away from a baseline recording—for a specified number of consecutive frames. The Goosecam has been tested in one participant who had voluntary control over piloerection (for an interesting exploratory investigation of this phenomenon, see Heathers et al., 2018), and was found to provide observations consistent with human judges (Benedek et al., 2010). It has since been used in several studies (Benedek & Kaernbach, 2011; Quesnel & Riecke, 2018; Sumpf et al., 2015; Wassiliwizky, Jacobsen, et al., 2017; Wassiliwizky, Koelsch, et al., 2017).

Another piloerection-monitoring device was proposed by Kim et al. (2014), and consists of a very thin, flexible, and compact sensor made of conductive polymer, which can be affixed to the skin to measure the physical deformation of its surface when goosebumps occur. The device was tested and validated by the authors, but while it represents an elegant solution, it remains unused in other studies to date, possibly because it requires resources which are less accessible than those needed to build a Goosecam.

### 4.3 Paradigms

Careful study design is required to investigate the different aspects of chills. A popular approach initially used by Blood and Zatorre (2001) and in many later studies (Laeng et al., 2016; Mori & Iwanaga, 2014, 2015, 2017; Sachs et al., 2016; Salimpoor et al., 2011; Salimpoor et al., 2009; Sumpf et al., 2015) requires participants to provide songs during which they often experience chills. They are then asked to listen to these songs and to songs provided by other participants, which act as a control. This has the clear advantages of ensuring that genuine chills are experienced, and excluding the possibility that the effects observed were simply due to the properties of each piece of music, since one participant's chills-inducing stimulus is another participant's control stimulus. Common findings in these studies are that participants experience more chills when listening to self-selected music, highlighting possible effects of familiarity (see Subsection 7.5), stylistic preference (see Subsection 8.2), and meaning (see Subsection 7.3), and demonstrating that chills are not caused by stimulus-driven properties alone. While this study design has been particularly fruitful because chills are often considered to be highly idiosyncratic (Nusbaum et al., 2014; Panksepp, 1995), it is important to bear in mind that chills most likely involve an interaction between listener, context, and music (see Subsection 7.6).

Other studies have compared or combined responses to self-selected stimuli and to stimuli selected by the researchers, either arbitrarily or following a pre-selection procedure (Benedek & Kaernbach, 2011; Carr & Rickard, 2016; Craig, 2005; Grewe et al., 2007; Mas-Herrero et al., 2014; Nagel et al., 2008; Panksepp, 1995; Quesnel & Riecke, 2018; Rickard, 2004; Wassiliwizky, Koelsch, et al., 2017; Weth et al., 2015), used experimenter-selected stimuli only (Balteș et al., 2011; Balteș & Miu, 2014; Bannister, 2019; Beier et al., 2020; Colver & El-Alayli, 2016; Grewe et al., 2011; Grunkina et al., 2017; Guhn et al., 2007; Jaimovich et al., 2013; Klepzig et al., 2020; Konečni et al., 2007; Schäfer & Sedlmeier, 2011; T. W. Schubert et al., 2018; Seibt et al., 2017; Seibt et al., 2018; Silvia et al., 2015; Solberg & Dibben, 2019; Strick et al., 2015; Wassiliwizky et al., 2015; Zickfeld, Schubert, Seibt, Blomster, et al., 2019), or participant-selected stimuli only (Craig, 2009; Fukui & Toyoshima, 2013; Wassiliwizky, Jacobsen, et al., 2017). Each of these approaches have distinct advantages and disadvantages, such as the degree of control over what the participants listen to, or how familiar they are with each piece of music. More specifically, experimenter-selected stimuli allow precise control over stimulus properties and familiarity, but may not always elicit chills, whereas participant-selected stimuli are very likely to induce genuine chills, at the cost of lower control over stimulus properties or familiarity.

Other paradigms provide better opportunities for making precise causal inferences, through direct manipulation of the stimuli (Bannister, 2020b; Bannister & Eerola, 2018; Juslin et al., 2014; Park et al., 2019), administration of substances thought to alter the experience of chills (Ferreri et al., 2019; Goldstein, 1980; Starcke et al., 2019), repeated presentation of the same stimuli to the same participant (Grewe et al., 2007), or more broadly, through the a priori design of clearly distinct experimental conditions (Beier et al., 2020; Egermann et al., 2011; Goodchild et al., 2019; Grewe et al., 2009a; Schoeller, Eskinazi, et al., 2018; Schoeller & Perlovsky, 2016; Sutherland et al., 2009). Note that here, we are referring to causal paradigms, and not necessarily to knowledge about what causes chills, which is why these studies are discussed in different sections of this article based on how relevant their findings are to each section. Such causal designs are clearly capable of providing more robust insight into chills than experiments providing only correlational evidence, although they come with their own set of challenges, such as manipulating stimuli while maintaining ecological validity and avoiding the introduction of confounding factors.

While less relevant to this review, it is worth mentioning a small set of studies that have used chills as an independent variable, leading to findings that chills had no effect on memory performance as measured by image recall (Carr & Rickard, 2016) or on craving reduction in abstinent individuals with alcohol use disorder (Mathis & Han, 2017), had an effect on gait, as seen by increased cadence and stride length, and reduced stride time (Park et al., 2019), did not improve mood or increase generosity, helpfulness, or prosocial behaviour (Konečni et al., 2007), but contradictorily, did promote altruistic behaviour

(Fukui & Toyoshima, 2014). Two devices have also been designed in an attempt to induce chills, through electrostatic force (Fukushima & Kajimoto, 2012) or coldness (Ishikawa et al., 2019), with the purpose of enhancing the emotional experience of music.

### 4.4 Summary

Self-reports and objective measures both provide distinct advantages, but also have their drawbacks. With self-report measures arise the issue of demand characteristics, through which the behaviour of participants can be influenced by the information they can infer about the experimental hypothesis (Juslin, 2016; Orne, 1962). Moreover, self-report measures are also subject to self-presentation biases and limited awareness of felt emotions, and providing them continuously or retrospectively can respectively cause issues with distraction or reliability (Zentner & Eerola, 2010). These problems do not arise with objective measures, but in the case of research on chills, such measures are currently limited to the detection of piloerection, which does not encompass the entirety of the experience of chills (see Subsection 2.2), potentially leading to increased type II error rates. Combining methodologies appears to be the best approach, and has been done in many studies. In terms of paradigms, causal approaches have gained traction. They are crucial if we are to gain a better understanding of the causes of chills, and should be used whenever possible in future research, along with naturalistic listening experiences to increase ecological validity (see Eerola, 2018; Hargreaves & North, 2010; Hodges, 2016), and longitudinal designs to study how experiences of chills change over time (see Greasley & Lamont, 2016).

## 5 Physiological correlates

Being involved in emotional reactions (see Subsection 3.1), chills are associated with autonomic nervous system activity (Kreibig, 2010), and are therefore accompanied by a set of physiological responses which have been studied extensively. We review these responses by examining how electrodermal, cardiac, and other physiological measures are associated with chills.

### 5.1 Skin measures

Electrodermal activity is typically decomposed into its tonic component, skin conductance level, reflecting slow, smooth changes in baseline activity, and its phasic component, skin conductance response, reflecting rapidly changing, event-related activity. Skin conductance level was found to increase around the onset of chills, either shortly before they occur (Grewe et al., 2009a) or shortly after (Benedek & Kaernbach, 2011; Mori & Iwanaga, 2017), though a comparable number of studies found no effects of chills on this measure (Balteș et al., 2011; Carr & Rickard, 2016; Jaimovich et al., 2013; Schäfer & Sedlmeier, 2011). The consensus is much more pronounced for skin conductance response, with many studies reporting associations with chills (Bannister & Eerola, 2018; Benedek & Kaernbach, 2011; Craig, 2005; Egermann et al., 2011; Grewe et al., 2011; Grewe et al., 2009a; Grewe et al., 2007; Guhn et al., 2007; Klepzig et al., 2020; Mas-Herrero et al., 2014; Mori & Iwanaga, 2014, 2015, 2017; Rickard, 2004; Sachs et al., 2016; Salimpoor et al., 2011; Salimpoor et al., 2009), and only three not detecting such associations (Blood & Zatorre, 2001; Carr & Rickard, 2016; Jaimovich et al., 2013). Specifically, skin conductance response has been found to increase shortly before (Egermann et al., 2011; Grewe et al., 2009a; Salimpoor et al., 2009) or after (Benedek & Kaernbach, 2011; Grewe et al., 2011; Mori & Iwanaga, 2017) the onset of chills, and to peak during (Craig, 2005; Salimpoor et al., 2009) or shortly after (Grewe et al., 2009a; Mori & Iwanaga, 2017) chills. In some of these studies, however, self-reported chills were only considered for analysis if accompanied by an increase in skin conductance response (see Subsection 4.1), which might have biased the results to some extent. Finally, peripheral skin temperature was found in some studies to decrease during chills (Salimpoor et al., 2009) or with chills intensity (Salimpoor et al., 2011), although others found no such association (Blood & Zatorre, 2001; Craig, 2005; Rickard, 2004).

## 5.2 Heart measures

Increases in heart rate (or decreases in interbeat interval—an inversely related variable) have generally been found to be associated with chills (Benedek & Kaernbach, 2011; Blood & Zatorre, 2001; Grewe et al., 2009a; Guhn et al., 2007; Mas-Herrero et al., 2014; Sachs et al., 2016; Salimpoor et al., 2011; Salimpoor et al., 2009; Sumpf et al., 2015), though, again, these findings have not always been replicated (Balteș et al., 2011; Carr & Rickard, 2016; Grewe et al., 2011; Jaimovich et al., 2013; Mori & Iwanaga, 2017; Rickard, 2004; Schäfer & Sedlmeier, 2011). Interestingly, in one study, heart rate was found to increase only for chills that involve piloerection (Sumpf et al., 2015). Decreases in blood volume pulse amplitude (Benedek & Kaernbach, 2011; Salimpoor et al., 2011; Salimpoor et al., 2009), increases in $E_K$, a specific ratio of cardiac amplitudes in the resting electrocardiogram associated with emotionality (Sumpf et al., 2015), respiratory sinus arrhythmia, and power in the low frequency of heart rate variability (Balteș et al., 2011) have also been associated with chills, while no effects were found for heart rate variability (Carr & Rickard, 2016), systolic blood pressure, diastolic blood pressure, power in the very low frequency of heart rate variability, and the ratio between low and high frequency powers of heart rate variability (Balteș et al., 2011).

## 5.3 Other measures

Empirical evidence is mixed on the relationship between chills and an increase in respiration rate, with some studies finding supporting evidence (Balteș et al., 2011; Salimpoor et al., 2011; Salimpoor et al., 2009), and others failing to identify such a relationship (Benedek & Kaernbach, 2011; Grewe et al., 2011; Mori &

Iwanaga, 2017; Sumpf et al., 2015). Respiration depth, however, has been found to increase in all (Benedek & Kaernbach, 2011; Blood & Zatorre, 2001; Grewe et al., 2009a) but one study (Mori & Iwanaga, 2017). Muscle tension, as measured by electromyography, increased when listening to self-selected music known to induce chills (Blood & Zatorre, 2001), but was not reported to increase with increased frequency of chills (Rickard, 2004). Salivary cortisol levels decreased when listening to music that induces chills (Fukui & Toyoshima, 2013) but not with increased frequency of chills (Rickard, 2004). Other salivary hormone levels showed different patterns, with increases in estradiol, and no changes in testosterone, though it is important to note that this was in response to listening to music self-selected as likely to elicit chills—occurrence of chills was not actually recorded in this study (Fukui & Toyoshima, 2013). Pupil diameter increased during chills, but this was not the case for eye blinks, saccade amplitude, or saccade dispersion (Laeng et al., 2016), and resting physiological state, recorded as a pre-experiment baseline, was found to be associated with the number of chills when listening to self-selected music (Mori & Iwanaga, 2014).

## 5.4 Summary

Overall, chills are associated with many physiological changes, and most often with increases in skin conductance response, heart rate, and respiration depth. However, the quality of the reviewed evidence must also be taken into account. Some studies systematically compared physiological responses in the presence or absence of chills (e.g., Benedek & Kaernbach, 2011; Craig, 2005; Grewe et al., 2011; Grewe et al., 2009a; Guhn et al., 2007; Mas-Herrero et al., 2014; Mori & Iwanaga, 2017; Salimpoor et al., 2009; Sumpf et al., 2015), while other studies were correlational in nature, or compared averaged responses at the song level rather than continuous responses at precise moments in time (e.g., Balteș et al., 2011; Carr & Rickard, 2016; Jaimovich et al., 2013; Rickard, 2004; Salimpoor et al., 2011; Schäfer & Sedlmeier, 2011). Due to these differences in experimental design, greater weight should be given to findings about the presence of effects for skin conductance level and heart rate, and the absence of an effect for respiration rate. However, these studies are still limited by a lack of replication using different methodological approaches.

More generally, the reviewed evidence is consistent with increases in self-reported arousal when experiencing chills (Balteș et al., 2011; Carr & Rickard, 2016; Grewe et al., 2009a; Mori & Iwanaga, 2015, 2017; Sumpf et al., 2015). However, the time course of physiological responses associated with chills is unclear, with changes in physiological arousal either preceding, co-occurring with, or following chills, making it difficult to assess whether arousal is a cause or a consequence of chills, or simply a co-occurring phenomenon (see Subsection 9.3). Physiological measures are sometimes thought to be relatively non-specific, and only indicative of a general state of arousal (Larsen et al., 2008; Panksepp & Bernatzky, 2002), but there is actually some degree of physiological response specificity, allowing particular response patterns to be associated with discrete emotions (Hodges, 2016; Kreibig, 2010). Further research using a wider range of physiological responses could help identify which emotions are most closely related to chills.

# 6 Neural correlates

The neural correlates of chills are discussed in many papers, particularly when referring to the results of Blood and Zatorre (2001) and Salimpoor et al. (2011). Some very thorough reviews explore the neuroscience of music and emotion in depth, with significant coverage of the neuroscientific literature on chills (e.g., Archie et al., 2013; Brattico et al., 2013; Brattico & Pearce, 2013; Chanda & Levitin, 2013; Habibi & Damasio, 2014; Koelsch, 2010, 2014; Salimpoor & Zatorre, 2013; Schaefer, 2017; Zatorre, 2003, 2015; Zatorre & Salimpoor, 2013). Therefore, this section of our review presents a brief summary of the main findings, examining how chills are associated with the basal ganglia and other neural structures, as well as results from lesion and neurochemical studies, and research on anhedonia.

## 6.1 Basal ganglia

Structures belonging to the basal ganglia have been repeatedly linked with chills. In the dorsal striatum, increases in activation have been found in the putamen and left caudate nucleus when comparing music listening with and without the experience of pleasant chills (Klepzig et al., 2020). Furthermore, in an earlier study, the right caudate nucleus showed increased activation in anticipation of chills, as well as a positive relationship between dopamine release and number of chills (Salimpoor et al., 2011). Effects have also been found in the ventral striatum, which showed increased activation in response to pleasant chills in a healthy control, but not in a patient with lesions following an extended stroke of the left middle cerebral artery (Grunkina et al., 2017). Activation in the left ventral striatum increased when listening to music that was self-selected to elicit pleasant emotional responses, including chills, and was positively correlated with ratings of chills intensity (Blood & Zatorre, 2001). Within the ventral striatum, the right nucleus accumbens showed increased activation during chills, and a positive relationship between dopamine release, intensity of chills, and degree of pleasure (Salimpoor et al., 2011), suggesting an involvement of this structure in processing the hedonic and reinforcing aspects of musical pleasure (Chanda & Levitin, 2013).

## 6.2 Other subcortical structures and cortical regions

In addition to the nucleus accumbens, associations with chills have been reported for a wide range of limbic and paralimbic structures, such as the amygdala (Griffiths et al., 2004; Grunkina et al., 2017) and the left hippocampus, both of which showed decreased activation as chills intensity increased (Blood & Zatorre, 2001), as well as the cingulate cortex (Blood & Zatorre, 2001), the insular cortex (Blood & Zatorre, 2001; Griffiths et al., 2004; Grunkina et al., 2017; Klepzig et al., 2020), and the orbitofrontal cortex (Blood & Zatorre, 2001), which all displayed increased activation with chills (or an impaired ability to experience chills for patients with an insular lesion—see Subsection 6.3), demonstrating a widespread involvement of the limbic system and associated cortical regions. Other brain structures and cortical regions have also shown increased activation with chills, such as the primary auditory cortex and the secondary somatosensory cortex (Grunkina et al., 2017), the thalamus (Blood & Zatorre, 2001; Grunkina et al., 2017; Klepzig et al., 2020), the dorsomedial midbrain, the supplementary motor area, the cerebellum (Blood & Zatorre, 2001), including the right cerebellar hemisphere (Klepzig et al., 2020), and the locus coeruleus, as indicated by pupillary dilation during chills (Laeng et al., 2016), as well as decreased activation for the ventromedial prefrontal cortex, the cuneus, and the precuneus (Blood & Zatorre, 2001)

## 6.3 Structural, neuropsychological, and neurochemical findings

White matter connectivity was investigated by Sachs et al. (2016), who reported increased tract volume from the posterior superior temporal gyrus to the anterior insula and medial prefrontal cortex—these tracts being part of the uncinate fasciculus, among others—in people who experience chills frequently and consistently, but no difference in corticospinal tract volume, suggesting that these differences are specific, and not a result of general differences in white matter connectivity (Sachs et al., 2016). Lesion studies have provided support for the involvement of these structures and tracts. A patient with lesions in the left insula and left amygdala exhibited impaired emotional processing of music, despite normal music perception and processing (Griffiths et al., 2004), and another patient with damage in the pyramidal tract, uncinate fasciculus, and left anterior insular cortex showed reports of chills intensity consistent with a healthy control, but diminished bodily responses as indexed by changes in skin conductance level and skin conductance response (Grunkina et al., 2017). Neurochemical findings provide some clarity on the role of endogenous opioids and dopamine. Chills were attenuated in three out of ten participants administered with naloxone, an opiate receptor antagonist (Goldstein, 1980)—a preliminary finding which received further support from a decrease in self-reported pleasure for pleasurable music after inducing anhedonia with naltrexone, a µ-opioid antagonist similar to naloxone (Mallik et al., 2017). Furthermore, the amount of time experiencing chills was higher than placebo following intake of levodopa, a dopamine precursor, and lower than placebo following intake of risperidone, a dopamine antagonist (Ferreri et al., 2019).

## 6.4 Anhedonia

The literature on anhedonia further supports the results of neuroimaging, neurochemical, and lesion studies. Higher physical anhedonia, characterised by diminished reward from physical and sensory experiences, has been associated with experiencing chills less often (Nusbaum et al., 2015), and shown to involve reduced activation in the left ventral striatum and increased activation in the ventromedial cortex (Dowd & Barch, 2012; Harvey et al., 2007; as cited by Nusbaum et al., 2015). Specific musical anhedonia, characterised by a failure to find music rewarding despite normal music perception and the absence of generalised anhedonia, can be measured with the Barcelona Musical Reward Questionnaire (Mas-Herrero et al., 2013), and has been found to be associated with fewer and less intense experiences of chills, and a lack of increase in skin conductance response, despite behavioural reports of chills by some anhedonic participants (Mas-Herrero et al., 2014). Interestingly, tract volume between the left superior temporal gyrus and the left nucleus accumbens was shown to be lower for participants with severe musical anhedonia (Loui et al., 2017), providing further support for the involvement of white matter connectivity between auditory and limbic structures.

## 6.5 Summary

Chills involve the recruitment of brain structures associated with emotion, reward, pleasure, reinforcement, motivation, arousal, and motor processes (Blood & Zatorre, 2001; Brattico et al., 2009; Chanda & Levitin, 2013; Vuust & Kringelbach, 2010), and display activation patterns consistent with the reward experienced in response to food, sex, and drugs, notably through the recruitment of dopaminergic and opioid systems (Blood & Zatorre, 2001; Chanda & Levitin, 2013; Mallik et al., 2017; Zatorre, 2003). Additionally, evidence suggests that individual differences in the experience of chills might be due, in part, to white matter connectivity between auditory and reward systems (Brattico, 2019; Hernández et al., 2019; Loui et al., 2017; Sachs et al., 2016).

Importantly, some of the neural correlates of chills are not specific to chills, but are also involved in pleasurable responses to music, even in the absence of chills (see Archie et al., 2013; Koelsch, 2010, 2014; Salimpoor et al., 2011). This implies that chills invoke a general-purpose network involved in pleasurable experiences of music, rather than dedicated neural machinery. Other limitations of this body of work include poor generalisability due to small sample sizes and participants sometimes being selected for their ability to reliably experience chills (e.g., Blood & Zatorre, 2001; Salimpoor et al., 2011), the poor time resolution of positron emission tomography, used in the study by Salimpoor et al. (2011), resulting in uncertainty about the precise timing of dopamine release (Habibi & Damasio, 2014; Vuust & Kringelbach, 2010), and finally, reliance on drawing reverse inferences about psychological mechanisms from observations of activation in brain areas subserving a broad range of psychological functions (Konečni, 2005; Logothetis, 2008; Poldrack, 2011). Overall, however, the consistency of the findings across a broad range of methods (neuroimaging, neurochemical, and lesion studies) provides strong support for the involvement of limbic and reward-related brain regions during chills.

# 7 Elicitors

The causes of chills fall into three broad categories: low-level acoustic elicitors, representing basic properties of the auditory signal, high-level musical elicitors, representing stimulus properties more specific to music, such as harmonic movement, and emotional elicitors, representing subjectively felt emotions in pieces of music. Understanding these causes is necessary in order to assess which psychological mechanisms might underlie chills, and to inform general psychological theories about chills (see Section 9). As a result, considerable attention has been given to identifying these elicitors, as reviewed in this section.

## 7.1 Acoustic elicitors

Chills have repeatedly been linked with dynamic acoustic changes, and most often when such changes are sudden (Guhn et al., 2007; Nagel et al., 2008; Sloboda, 1991). More specifically, increased loudness or more frequent peaks in loudness were found around the onset of chills (Beier et al., 2020; Grewe et al., 2007; Guhn et al., 2007; Nagel et al., 2008), particularly in the 920–4400 Hz band (Nagel et al., 2008). Loudness was also associated with continuous ratings of chills intensity (Bannister & Eerola, 2018), and experimentally increasing the loudness of a musical passage known to often induce chills and likely to engage *auditory looming* (see Subsection 9.4) resulted in more frequent experiences of chills (Bannister, 2020b). Pleasure could be a mediating factor, however, with changes in volume leading to increased pleasure in some cases (Grewe et al., 2007), but decreased in others (Bannister, 2020b). Chills have also been shown to co-occur with higher event density (Bannister & Eerola, 2018; Nagel et al., 2008), expansion of the frequency range in the high or low register (Guhn et al., 2007), higher spectral centroid and spectral flux (Bannister & Eerola, 2018), increased roughness, dissonance, or fluctuation strength (Bannister & Eerola, 2018; Beier et al., 2020; Grewe et al., 2007; Nagel et al., 2008; Park et al., 2019), and increased sharpness or brightness (Bannister & Eerola, 2018; Beier et al., 2020; Grewe et al., 2007), although, for one specific song, increasing brightness was found to reduce the frequency of chills (Bannister, 2020b).

## 7.2 Musical elicitors

A number of features more specific to music have also been identified as potential causes of chills, expanding on what was initially described as "dramatic peaks and valleys in music" (Goldstein, 1980, p. 127). Related to increases in loudness discussed in the previous paragraph, crescendi, build-ups, and climaxes have been linked with chills (Bannister, 2020a; Bannister & Eerola, 2018; Panksepp, 1995; Solberg & Dibben, 2019). In addition to sudden dynamic changes, Sloboda (1991) identified several structural characteristics of musical excerpts that elicit chills, such as new or unprepared harmonies, sudden textural changes, melodic appoggiaturas, enharmonic changes, specific melodic or harmonic sequences, or prominent musical events arriving earlier than prepared for, among others.

Similar melodic and harmonic properties, including structural transitions and alterations such as changes in tonality, were subsequently associated with chills in several empirical studies (Bannister, 2020a; Bannister & Eerola, 2018; Guhn et al., 2007; Mlejnek, 2013; Schurtz et al., 2012), in addition to rhythmic properties (Schurtz et al., 2012; Solberg & Dibben, 2019), although the two latter studies lack specific detail about which rhythmic properties were involved. A recurrent theme is textural changes (Sloboda, 1991; Solberg & Dibben, 2019), particularly with the entrance of new instruments, and the alternation, contrast, or communion between solo and accompanying instruments (Bannister, 2020a; Bannister & Eerola, 2018; Goodchild et al., 2019; Guhn et al., 2007; Mlejnek, 2013), which are considered particularly pleasurable by listeners (Grewe et al., 2007). Voice and lyrics have also been identified as potent elicitors of chills (Bannister, 2020a; Schurtz et al., 2012), and some researchers have identified passages from slow movements (Guhn et al., 2007) and virtuosity (Mlejnek, 2013) as possible causes of chills.

Finally, in a causal study by Bannister and Eerola (2018), chills were found to happen less frequently, and to be rated as less intense, when specific passages known to often elicit chills were removed from three pieces of music. Interestingly, as opposed to chills, skin conductance response did not diminish when these passages were removed. This suggests that physiological arousal is dependent on local musical context, and possibly linked to the anticipation of chills. Another point of interest reported by Bannister and Eerola (2018) is that acoustic and musical elicitors might be intrinsically related, since the entrance of new instruments, for instance, would naturally come along with dynamic and spectral changes. Research that comprehensively teases apart the effects of acoustic and musical elicitors is needed to better understand how stimulus properties influence the occurrence of chills.

## 7.3 Emotional elicitors

Chills can also arise from the perception of emotions expressed by music, which, for present purposes, can be broadly grouped into valence, intensity, and meaning. While frequency of self-reported chills has been found to increase when listening to music rated as positively valenced (Grewe et al., 2011), associations between chills and perceived sadness in female participants were found by Panksepp (1995) following a series of experiments. In this study, however, both happy and sad music were reported to elicit chills, as was the case in other studies linking both positive and negative perceived emotions with chills (Bannister, 2020a; Mori & Iwanaga, 2017). Rather than valence, greater perceived emotional intensity, whether positively or negatively valenced, has often been identified as a possible cause of chills, whether it is referred to as such (Bannister & Eerola, 2018; Grewe et al., 2009a), as emotional power (Rickard, 2004), as perceived emotional content (Panksepp, 1995), as emotionality (Beier et al., 2020), or as the climactic stage of an aesthetic experience (Panzarella, 1980).

Finally, related to the effect of lyrics discussed in the previous subsection (Bannister, 2020a; Schurtz et al., 2012), chills have been found to be associated with the perception of meaning in music, whether it is meaning of lyrics (Bannister, 2020a), personal meaning (Craig, 2009; Goldstein, 1980), or extra-musical meaning, such as pride or patriotism (Mlejnek, 2013). Notably, some studies of the effects of meaning have focused on priming effects, and resulted in conflicting perspectives. Specifically, while there was little to no effect of presenting various types of priming stimulus (national anthems, stories, architectural objects, paintings) on the frequency or duration of chills when subsequently listening to a piece of music (Konečni et al., 2007), being exposed to a complex, existential statement, as opposed to an incoherent statement, increased the number of chills experienced when watching subsequent video clips (Schoeller, Eskinazi, et al., 2018; Schoeller & Perlovsky, 2016). Interestingly, Konečni et al. (2007) also observed that there was no priming effect of experiencing chills themselves on subsequent experiences of chills, whereas frequency of chills has been found to increase (Benedek & Kaernbach, 2011) or decrease (Laeng et al., 2016) with trial number during experiments (and therefore, following previous occurrences of chills), highlighting a lack of consensus on the matter.

## 7.4 Underlying mechanisms

When it comes to understanding how these various elicitors might cause chills, it is useful to consider potential underlying psychological mechanisms. A useful framework for doing so comes from an extensive body of work which sought to provide a unified theory of evoked musical emotions in the form of a set of underlying mechanisms (Juslin, 2013; Juslin & Västfjäll, 2008), the diversity of which was echoed by Huron (2016) when discussing the range of ways in which sounds are thought to evoke pleasure. It could be that these mechanisms are also involved in the experience of chills, by evoking emotions which would in turn induce chills, or by directly inducing chills, but not fully fledged emotional experiences (see Subsection 3.1).

In this framework, *brain stem reflex* refers to the process by which low-level acoustic features quickly and automatically elicit emotions when exceeding a threshold value (Juslin, 2013), and would provide a reasonable explanation as to why acoustic elicitors such as sudden changes in loudness or dissonance might cause physiological arousal and chills (L. Harrison & Loui, 2014; Juslin et al., 2014). *Musical expectation* benefits from a long-standing theoretical background (Hanslick, 1854; Meyer, 1956), and is based on the hypothesis that developing expectations follows a process of probabilistic learning of the statistical regularities in musical structure (Pearce, 2018; Saffran et al., 1999), which allows learned expectations to be violated, delayed, or confirmed, resulting in induced emotional and aesthetic responses (Cheung et al., 2019; Gold et al., 2019; Huron, 2006; Juslin, 2013; Steinbeis et al., 2006). Musical expectation has often been posited as a cause of chills (L. Harrison & Loui, 2014; Huron, 2006; Huron & Margulis, 2010; Juslin, 2013; Juslin & Västfjäll, 2008; McDermott, 2012; Mencke et al., 2019; Pearce & Wiggins, 2012; Salimpoor et al., 2011; Sloboda, 1991), and indeed, the majority of the musical elicitors discussed in this section could engage such a mechanism. Interestingly, Levinson (2006) suggested that there might be two types of chills, the first type induced timbrally or dynamically, and the second type induced melodically, harmonically, or rhythmically. This is consistent with the possible involvement of brain stem reflex, on the one hand, and musical expectation, on the other.

Other mechanisms underlying emotional responses to music have also been discussed in relationship to chills, such as *episodic memory* (Goldstein, 1980), *evaluative conditioning*, or *emotional contagion* (L. Harrison & Loui, 2014), all of which have been linked speculatively by these authors to some of the emotional elicitors discussed in the previous subsection. Paradoxically, when underlying mechanisms were explicitly investigated, either systematically (Juslin et al., 2014) or through self-reports (Bannister, 2020a; Bannister & Eerola, 2018), emotional contagion was strongly linked to chills, but brain stem reflex and musical expectation were not. These results, however, could reflect the distinct possibility that the experimental manipulations of the musical stimuli did not adequately target the mechanisms in question, that listeners do not have sufficient conscious access to the reasons why they experience chills to be able to self-report them, or that such conscious access varies between mechanisms. Further investigation is therefore needed to obtain conclusive answers about the psychological mechanisms that underlie chills.

## 7.5 Associated factors

There exist other factors that potentially contribute to the elicitation of chills. While these have rarely been the primary topic of investigation, they are often reported, and provide useful context to the findings discussed in this section. Some authors covered listening situations, comparing occurrences of chills when listening to music alone or with others. In most cases, no differences were found (Egermann et al., 2011; Nusbaum et al., 2014; Sutherland et al., 2009), although peaks in skin conductance response were higher during chills when listening alone than when listening in a group (Egermann et al., 2011), and survey respondents reported most experiences of chills to happen during solo listening (Bannister, 2020a). These findings might reflect an effect of attention (Beier et al., 2020; Nusbaum et al., 2014), possibly related to alcohol intake being found to reduce frequency of chills (Starcke et al., 2019), which would provide further support for the suggested role of attention in aesthetic responses (see Subsection 3.3).

Another important effect is that of repetition and familiarity. Listening to the same piece of music several times within a single experimental session was not found to affect the frequency or intensity of chills (Balteș et al., 2011; Bannister, 2020b; Blood & Zatorre, 2001), but doing so every day over a week led to reduced frequency of chills (Grewe et al., 2007), possibly due to habituation, although this longitudinal effect was investigated in only one participant. Over longer time scales, chills have been reported to be a reliable response, and even to grow with repeated listening (Sloboda, 1991). More generally, conflicting effects of familiarity have been identified, with some studies reporting more occurrences of chills for familiar stimuli (Craig, 2005; Grewe et al., 2009a; Panksepp, 1995; Rickard, 2004; Weth et al., 2015), and other studies reporting no effects of stimulus familiarity (Bannister, 2019; Bannister & Eerola, 2018; Benedek & Kaernbach, 2011; Colver & El-Alayli, 2016; Guhn et al., 2007; Rickard, 2004; Wassiliwizky et al., 2015), although some of these studies featured stimuli which were either all very familiar (Benedek & Kaernbach, 2011), or very unfamiliar (Colver & El-Alayli, 2016; Guhn et al., 2007). Familiarity has been argued to be a strong driver of aesthetic experiences, in conjunction with surprise, complexity, and expectation (Greasley & Lamont, 2016; Salimpoor et al., 2015; Verhaeghen, 2018), and could contribute to the elicitation of chills by increasing recognition of meaning in music (see Subsection 7.3) or by promoting a conflict between *schematic* and *veridical* expectation (Bharucha, 1994; Huron, 2006; Miranda & Ullman, 2007; Salimpoor et al., 2015), allowing unconscious surprise, caused by schematically unexpected events, to continue to occur in very familiar music, which would be veridically highly expected. This remains speculative, until further empirical research provides greater clarity on the association between familiarity and chills.

### 7.6 Summary

Some authors have reported a lack of clear stimulus-response pattern with the experience of chills (Bannister, 2020a; Grewe et al., 2007; Nagel et al., 2008), and while it is certainly true that a specific musical passage does not reliably cause chills for all people (see Subsection 4.3), evidence strongly points towards a set of acoustic, musical, and emotional elicitors being involved in the experience of chills, including dynamic changes, increased roughness, crescendi, unexpected structural changes, textural changes, and perceived emotional intensity. Through underlying mechanisms, such as brain stem reflex and expectation, and associated factors, such as attention and familiarity, it is likely that, as is the case with aesthetic and emotional responses to music (Gabrielsson, 2011; Hargreaves, 2012; Juslin, 2013; Juslin & Västfjäll, 2008; Scherer et al., 2001), chills rely on an interaction between listener (see Section 8), context (about which there is currently relatively little research, although see Subsection 7.5), and music (this section). Importantly, most of the research discussed in this section relies on correlational evidence, which weakens its strength. However, efforts have been made in recent research to use systematic manipulations in order to establish causality (see Subsection 4.3), resulting in a more robust understanding of the causes of chills.

## 8 Individual differences

While most people seem to have the ability to experience chills when listening to music (see Subsection 2.3), not everyone can or does so equally often. As a result, there has been some interest in identifying how individual differences might affect the prevalence of chills and the frequency of experiencing them. In this section, we review the evidence on the role played by gender, age, musical training, and personality differences in the experience of chills.

## 8.1 Gender, age, and musical training

Panksepp (1995) identified in a series of experiments that women find sad music more likely to cause chills than men, and vice versa for happy music, among other findings showing, especially for women, a relationship between chills and perceived sadness. Similarly, Benedek and Kaernbach (2011) detected an effect of gender, with more women experiencing piloerection than men when listening to music and film audio, although the study involved an uneven gender ratio. The vast majority of studies that analysed the effect of gender, however, have reported no influence on chills (Bannister, 2019; Goldstein, 1980; Grewe et al., 2009a; Grewe et al., 2007; Guhn et al., 2007; N. R. Harrison & Clark, 2016; Mlejnek, 2013; Mori & Iwanaga, 2014; Rickard, 2004; Silvia & Nusbaum, 2011; Starcke et al., 2019; Sutherland et al., 2009; Zickfeld, Schubert, Seibt, Blomster, et al., 2019). The effect of age on chills is less clear. Correlations with age have been found for some (e.g., goose pimples) but not all (e.g., shivers down the spine) physiological reactions to music related to chills (Mlejnek, 2013), and age positively predicted a small amount of variance in the number of chills experienced during an opera performance (Balteș & Miu, 2014), whereas no effect of age was identified by Grewe et al. (2009a), Mori and Iwanaga (2014), Starcke et al. (2019), and Zickfeld, Schubert, Seibt, Blomster, et al. (2019). Regarding effects of musical training, Nusbaum and Silvia (2011) found that playing an instrument is a significant predictor of the frequency of experiences of chills, while Beier et al. (2020) reported effects of Western music theory knowledge on chills experienced when listening to Western, Indian, but not Chinese music. However, other empirical evidence does not support an effect of musical training or musical sophistication (Müllensiefen et al., 2014) on chills (Bannister & Eerola, 2018; Grewe et al., 2009a; Guhn et al., 2007; Rickard, 2004). It is important to note that most of these findings were not hypothesis-driven and there is very little theoretical basis for hypothesising effects of gender, age and musical training on chills. Considering this limitation, as well as the limited scope of some of the results (discussed above), it is reasonable to assume that, for the most part, chills are experienced independently of gender, age, and musical training.

## 8.2 Personality correlates

By far the most documented personality correlate of the experience of chills is openness to experience—a Big Five personality trait characteristic of individuals who are curious, innovative, imaginative, sensitive to the arts, and who experience a wide range of feelings and emotions (McCrae, 2007). The relationship between chills and openness to experience has been identified in many studies (Bannister, 2020a; Colver & El-Alayli, 2016; Maruskin et al., 2012; Mori & Iwanaga, 2015; Nusbaum & Silvia, 2011; Silvia et al., 2015; Silvia & Nusbaum, 2011; Sumpf et al., 2015), though it was ambiguous in some cases (Mori & Iwanaga, 2015; Sumpf et al., 2015), and not present in others (Mathis & Han, 2017; Rickard, 2004; Starcke et al., 2019). Importantly, the NEO Personality Inventory and the NEO Five-Factor Inventory (Costa & McCrae, 1992) used in the majority of these studies both include an item about experiencing chills, which counts towards openness to experience. This raises the concern that the empirical relationship between chills and openness to experience might be driven by the contribution of this item towards the scale. However, this seems not to be the case, because the item about chills is highly correlated with the sum of the remaining items on the openness to experience scale, as shown by corrected item-total correlations for this trait. Moreover, this analysis revealed that out of all items, the one about chills is the most highly correlated with the rest of the scale, making it the best cross-cultural indicator of openness to experience (McCrae, 2007). In addition, this item was confirmed to be related to the number of chills experienced in a lab environment (Colver & El-Alayli, 2016). The other Big Five traits have also been investigated, and found to predict some of the variance in the frequency of experiencing chills when taken together (Nusbaum & Silvia, 2011; Silvia & Nusbaum, 2011), and individually in the case of extraversion (Maruskin et al., 2012; Rickard, 2004; Sumpf et al., 2015), neuroticism (Maruskin et al., 2012; Silvia et al., 2015; Sumpf et al., 2015), and agreeableness, though the relationship for the latter has been found to be both positive (Sumpf et al., 2015) and negative (Maruskin et al., 2012). Agreeable individuals were also found to be more likely to experience chills with piloerection rather than without (Sumpf et al., 2015).

Aside from the Big Five traits, many personality factors have been investigated. Experiencing chills was found to be associated with being more observing and judging (N. R. Harrison & Clark, 2016), less susceptible to anger (Laeng et al., 2016), more likely to follow the *music-empathising* cognitive style of music listening, which is linked with a greater focus on emotional content (Linnemann et al., 2018), and more likely to listen to music in order to reduce negative affect rather than to stimulate fun (Starcke et al., 2019). There are conflicting results about the effects of reward dependence and sensitivity (Bannister, 2020b; Grewe et al., 2007; Mori & Iwanaga, 2015, see Subsection 6.4 for the relationship between chills and anhedonia), thrill and adventure seeking (Grewe et al., 2007; Mathis & Han, 2017), stylistic preference (Bannister & Eerola, 2018; Nusbaum & Silvia, 2011), and *aesthetic fluency*, a measure of expertise in the arts (N. R. Harrison & Clark, 2016; Silvia & Nusbaum, 2011), and no effects were detected for fluid intelligence (Silvia & Nusbaum, 2011), mood (Balteș & Miu, 2014), or vividness of visual imagery (Balteș & Miu, 2014).

Interestingly, when distinguishing between different categories of chills (see Subsection 2.4), personality correlates differ. Goosetingles have been associated with extraversion, approach temperament, and positive emotionality, while coldshivers have been linked with neuroticism, avoidance temperament, and negative emotionality (Maruskin et al., 2012). Similarly, while there appears to be no effect of trait empathy on chills as a single construct (Balteș & Miu, 2014; Bannister, 2020b), empathy has been found to be associated with moving chills, but not cold or warm chills (Bannister, 2019), echoing the results of a meta-analysis in which trait empathic concern, associated with the state of being moved, has been linked to chills (Zickfeld et al., 2017).

### 8.3 Summary

In general, evidence for the influence of individual differences on the experience of chills is mixed. This might be a consequence of most of these individual differences being studied in the context of exploratory research with little theoretical basis, with the exception of some of the Big Five personality traits (including openness to experience), as well as reward sensitivity, stylistic preference, and trait empathy. Regardless, from the totality of the evidence reviewed, it is now well established that openness to experience plays a role, and in more general terms, that personality differences affect who experiences chills, how often they are experienced, and, to some extent, which kind of chills is experienced. This should be taken into consideration when researching chills, because individuals might react differently to various experimental situations, based on their personality characteristics.

## 9 Theories

The evidence reviewed so far mostly addresses what chills are, and how they are elicited, but there remains the broader question of why chills occur. This final section surveys current psychological theories about their origin. Most of these theories are expressed in terms of the evolutionary basis of chills and they tend to overlap partially to varying degrees while also generally possessing distinctive features. It is therefore important in the context of this review to clearly and carefully delineate these theories. All of the theories are speculative to some degree. It is because of their speculative nature that we are closing rather than opening this review with these theoretical perspectives. At this point in time, none of the theories reviewed below have sufficient experimental support to provide a robust platform for scaffolding and interpreting the empirical literature as a whole. However, having surveyed the existing empirical literature, there is value in considering the extent to which empirical results to date corroborate or refute the predictions of these theories and the experimental evidence required for more conclusive assessment. With these goals in mind, we evaluate in this section theories proposing that chills are associated with separation calls, the emotional state of being moved, peak arousal, contrastive valence, and knowledge instinct.

### 9.1 Separation call

The idea behind the *separation call* theory is that, in many animal species, separation calls are used to motivate parents to locate their offspring who might have become lost. According to the theory, this need for social reunion is driven by a feeling of coldness elicited by separation calls and leading to piloerection, potentially caused by an overlap between brain functions governing thermoregulation and social bonding, thereby providing an evolutionary explanation for the purpose of chills (Panksepp, 1995, 2009; Panksepp & Bernatzky, 2002). This theory was proposed following early findings suggesting that chills are more likely in women, with music that is familiar, perceived as sad, and includes high-pitched crescendi, which could be respectively accounted for by mothers being more susceptible to separation calls, by social attachment being a learned behaviour in mammals, by sadness due to potential loss providing the emotional context for potential reunion, and by the acoustic characteristics of separation calls, according to Panksepp (1995). As discussed earlier in this review, however, the effects of gender (see Subsection 8.1), familiarity (see Subsection 7.5), and stimulus valence (see Subsection 7.3) are far from clear-cut, and the diversity in possible elicitors of chills cannot be fully explained by a similarity with separation calls (see Subsections 7.1 and 7.2).

Some researchers have argued that chills are indeed related to closeness and social bonding (Bicknell, 2007; Maruskin et al., 2012), linked to physiological changes consistent with a state of sadness (Benedek & Kaernbach, 2011), and that there might be an overlap between thermoregulatory and social functions (for a brief review, see Bannister, 2019). However, critics of the separation call theory have argued that it fails to account for the possible existence of different types of chills (Levinson, 2006; see also Bannister, 2019; Maruskin et al., 2012), that it is not consistent with the personality correlates of individuals most susceptible to experiencing chills (McCrae, 2007), that there is a lack of clarity about which stimulus properties would reflect separation calls (Bannister, 2020a), and that there is no evidence for the occurrence of chills in response to separation calls in nonhuman primates (Altenmüller et al., 2013). Despite an attempt to provide causal support (briefly described in Panksepp & Bernatzky, 2002, pp. 143–144) for the separation call theory, it does not fully account for current findings in the literature, and a clearer consensus for its supporting evidence would be needed to consider the theory even as a partial, if not complete, explanation for the occurrence of chills.

## 9.2 Being moved

Other theories have proposed that chills are related to the emotional state of *being moved*. Originating in an identified relationship between moving music and chills (Goldstein, 1980; Panksepp, 1995; Panksepp & Bernatzky, 2002), the concept found itself included in the *aesthetic trinity* of Konečni (2005), which comprises awe, being moved, and chills. Within the framework of the aesthetic trinity theory, being moved is often accompanied by chills, although both responses can occur independently, and the rarer response, awe, is always accompanied by experiences of being moved and chills (Konečni, 2005, 2007, 2008, 2013; Konečni et al., 2007). There is empirical support for a relationship between awe and chills (Cotter et al., 2018; Maruskin et al., 2012; Quesnel & Riecke, 2018; Schurtz et al., 2012; Silvia et al., 2015), but despite claims that experiencing aesthetic awe results from an evolutionary process of sexual selection (Konečni, 2005), the theory fails to clearly outline mechanisms for the occurrence of chills (Branković, 2013).

In another line of research, being moved has been included in the construct named *kama muta*, which represents a positive feeling, often involving tears, chills, and a subjective feeling of warmth in the chest, as a result of experiencing or observing an increase in communal sharing or closeness, and is associated with trait empathic concern (Fiske et al., 2019; T. W. Schubert et al., 2018; Seibt et al., 2018; Zickfeld, Schubert, Seibt, Blomster, et al., 2019; Zickfeld et al., 2017, 2019). While the experience of kama muta is not restricted to music listening, the co-occurrence of chills and tears, notably, is well documented in the music psychology literature (Bannister, 2019; Cotter et al., 2018; Mori & Iwanaga, 2017; Scherer et al., 2001; Strick et al., 2015).

More generally, there have been many theoretical (e.g., Menninghaus et al., 2015) and empirical (Bannister, 2019, 2020a; Bannister & Eerola, 2018; Benedek & Kaernbach, 2011; Eerola et al., 2016; Panksepp, 1995; Seibt et al., 2017; Strick et al., 2015; Vuoskoski & Eerola, 2017; Wassiliwizky, Jacobsen, et al., 2017; Wassiliwizky, Koelsch, et al., 2017; Wassiliwizky et al., 2015; Weth et al., 2015) associations between chills and being moved, with additional links to liking and perceived sadness. The aesthetic trinity and kama muta frameworks do not propose fully-fledged mechanisms explaining the relationship between being moved and chills, and furthermore, there is little detail about the evolutionary mechanisms which could underlie that relationship. However, the extent of the discourse is such that it seems appropriate to include the emotional state of being moved in this section, and fleshing it out in more detail should be considered as a promising avenue for future research.

## 9.3 Peak arousal

Motivated by a series of empirical findings (Grewe et al., 2009a; Grewe et al., 2007; Guhn et al., 2007; Rickard, 2004; as cited by Benedek & Kaernbach, 2011), the *peak arousal* hypothesis was proposed, advancing that chills occur when a threshold in emotional and physiological arousal is exceeded (Benedek & Kaernbach, 2011). A closely related idea was first formulated by Blood and Zatorre (2001), who suggested that chills can be experienced once a certain level of pleasure and emotional intensity is reached, and indeed, many empirical studies have subsequently used chills as an indicator of pleasurable responses to music, and uncovered relationships between emotional intensity, pleasure, and chills (see Subsections 3.2 and 7.3).

Similarly, chills have been shown unequivocally to be associated with physiological arousal (see Section 5), but this theory posits more specifically that chills are indicators of peak emotional and physiological arousal. While some studies have investigated the time-course of such peak responses, there is a lack of agreement about their specific timing with respect to the onset of chills (see Subsection 5.1). Furthermore, little is known about whether or not peaks of arousal, pleasure, or emotional intensity can occur in the absence of chills, which raises the question of whether chills are a cause or a consequence of emotional and physiological arousal. In their study, Benedek and Kaernbach (2011) found some evidence consistent with the peak arousal hypothesis, but also suggested that rapid, shallow breathing during chills is required to further support the hypothesis. Such breathing patterns were not observed in their study, or in most studies of respiration rate and depth during experiences of chills while listening to music (see Subsections 5.3 and 5.4). Overall, the empirical data available to date do not clearly support or refute the peak arousal hypothesis, and further systematic study is needed in order to fully examine the time-course of emotional and physiological arousal, as well as pleasure and emotional intensity, in the presence and absence of chills.

## 9.4 Contrastive valence

It has also been proposed that chills can be elicited by musical expectations, most notably through a process called *contrastive valence*. This process relies on *ITPRA*, a theory of expectation proposed by Huron (2006), according to which responses to a situation are separated into *imagination* and *tension*, its pre-outcome components, and *prediction*, *reaction*, and *appraisal*, its post-outcome components. When listening to music, chills are thought to occur when a rapid, unconscious fear response due to an unexpected outcome causes piloerection, which is subsequently followed by a neutral or positive conscious appraisal of musical sounds as a safe stimulus, leading to pleasure due to the positive contrast in valence between these two responses (Huron, 2006; Huron & Margulis, 2010). According to the theory, pleasurable chills in response to an unexpected outcome, musical or not, reflect an exaptation of vestigial thermoregulation and intimidation responses, drawing their adaptive value from promoting attention and information processing, rewarding and reinforcing learning when faced with inaccurate predictions, facilitating memory formation, and driving curiosity to detect new, surprising patterns, through the recruitment of the dopaminergic reward system (see Section 6), in order to promote more effective decision making, thereby leading to positive future outcomes (Altenmüller et al., 2013; Grewe et al., 2007; Huron, 2006; Huron & Margulis, 2010; Maruskin et al., 2012; Wassiliwizky, Koelsch, et al., 2017).

As discussed previously, many empirical findings are consistent with a role of schematic and veridical expectation in the experience of chills (see Subsections 7.2, 7.4, and 7.5). There are also distinct subjective, physiological, and neural differences between pre-outcome and post-outcome reactions when experiencing chills (Bannister & Eerola, 2018; Grewe et al., 2009a; Salimpoor et al., 2011; Wassiliwizky, Koelsch, et al., 2017), but these findings lack the temporal precision to fully support the exact time-course proposed by the ITPRA theory. In addition, while the relationship between expectation and pleasure has been explicitly investigated (Cheung et al., 2019; Gold et al., 2019), comparable studies have yet to be conducted on the relationship between expectation and chills. Critics of the theory argue that the lack of a universal stimulus-response pattern for chills renders fear unlikely to be the primary evolutionary cause of chills (Bannister, 2020a; Grewe et al., 2007; Nagel et al., 2008). However, this fails to account for the fact that different individuals can experience fear in response to different stimuli, based on experience and circumstances. Moreover, if expectation is involved, we would expect to see individual differences due to stylistic enculturation (Pearce, 2018; and for partial support of an effect of stylistic knowledge, see Beier et al., 2020). As with the other theories reviewed so far, however, contrastive valence doesn't fully account for the experience of chills, notably by failing to provide an explanation for chills caused by the emotional *expressiveness* of music (Levinson, 2006) and emotional elicitors (see Subsection 7.3).

Related to a fear-based response due to expectation mechanisms, it has recently been proposed that *auditory looming* is a possible cause of chills, presumably reflecting an adaptive need to perceive and signal an approaching threat (Bannister, 2019, 2020b; Bannister & Eerola, 2018). This theory, linked to the role of vigilance in expectation (Huron, 2006), could explain how crescendi and sudden increases in loudness might cause chills (see Subsections 7.1 and 7.2), and has received recent support from an experiment showing that manipulating loudness affects the occurrence of chills (Bannister, 2020b). However, the auditory looming theory does not naturally explain the pleasure often associated with chills, and it remains to be determined whether or not this can be attributed to contrastive valence.

## 9.5 Knowledge instinct

According to the *knowledge instinct* theory (see Schoeller, Perlovsky, & Arseniev, 2018), humans are driven to learn by modifying mental representations in order to match patterns in perceived stimuli. *Knowledge acquisition* consists of the creation and improvement of these representations, and knowledge instinct is the fundamental motivation for knowledge acquisition. Emotions arise from satisfaction or dissatisfaction of knowledge instinct, or in other words, from the congruence or incongruence between bottom-up sensory signals and top-down mental models. Positive aesthetic emotions occur when congruence remains high, and when content at the top of the cognitive hierarchy is engaged, possibly resulting in chills and experiences of the sublime (Schoeller, Eskinazi, et al., 2018; Schoeller & Perlovsky, 2016; Schoeller, Perlovsky, & Arseniev, 2018). In other words, chills can occur if stimuli that are relevant to important abstract concepts, such as meaning, are accurately predicted and understood. This theory has also been expressed in terms of an interaction between environment and encoded schema (Pelowski et al., 2017; Pelowski et al., 2018).

While this theory could account for the relationship between chills and the perception of meaning (see Subsection 7.3), and has received tentative support from the effect of the coherence of a priming statement on subsequent experiences of chills when watching video clips (Schoeller, 2015; Schoeller, Eskinazi, et al., 2018; Schoeller & Perlovsky, 2016), empirical corroboration remains limited due to a relative lack of diversity in the supporting evidence and the difficulty of deriving specific predictions from the theory about the precise timing of chills. Furthermore, the theory is ambiguous about whether chills occur when learning is required or when it is unnecessary (Pelowski et al., 2018), therefore making it unclear how to reconcile the theory with findings showing that chills occur in response to unexpected musical events (see Subsection 7.2).

## 9.6 Summary

At present, theoretical accounts for chills lag behind the empirical evidence in terms of their breadth, depth, degree of empirical corroboration, and ability to make clear and distinctive empirical predictions. Considering the diversity of empirical findings about chills, it seems unlikely that a single theory could provide an adequate explanation for why they occur. There is currently little empirical evidence that specifically supports the separation call and knowledge instinct theories. Taken together, however, contrastive valence, peak arousal and pleasure, and the emotional state of being moved could account for much of the empirical evidence. It therefore seems plausible that competing theories based on evolutionary expectation and social processes might together explain the diversity in elicitors and personality characteristics involved in the experience of chills (see Bannister, 2019).

It is worth emphasising again that all the theories reviewed here are speculative, and would greatly benefit from the use of cross-cultural (see Beier et al., 2020), and developmental research, both of which (and ideally in combination) would provide evidence regarding the role of culturally-embedded learning in determining the elicitors and experience of chills, as well as any potential evolutionary basis for their existence. In addition, hypothesis-based experiments are needed for further corroboration. In particular, the individual theories make different predictions about the psychological circumstances in which chills would be experienced—during an experience of being moved (due to social closeness and empathy), during an experience of contrastive valence or auditory looming, or during an experience of high levels of emotional arousal, intensity, or pleasure. Empirical experiments that test these predictions against one another are necessary to provide further clarity on the theoretical basis of chills. Again, we would emphasise that it seems very possible that more than one psychological mechanism will be required to account for different kinds of chills.

# 10 Conclusion

## 10.1 Findings

In this article, we have conducted an integrative, critical, and exhaustive review of the current literature on chills experienced in response to music listening, with the purpose of establishing a solid basis for future research. Theoretical and empirical findings were summarised through each section, leading to the conclusion that chills are a relatively frequent psychophysiological response which can include piloerection (Section 2), and a pleasurable, though not essential, component of emotional and aesthetic responses (Section 3), which have been studied using both subjective and objective measures, with a recent focus on causal approaches (Section 4). They are associated with physiological changes and increased arousal (Section 5), recruit brain structures and systems relevant to emotion, reward, and motivation (Section 6), can be elicited by acoustic, musical, and emotional stimulus-driven properties (Section 7), and are influenced by personality differences, and especially openness to experience (Section 8). Finally, theoretical accounts suggest that they may involve evolutionary mechanisms based on expectation and social processes (Section 9).

### 10.2 Recommendations

We highlighted areas of particular interest for future research on chills. Notably, we recommended that piloerection should not be used as the sole indicator of chills (Subsection 2.2), that chills should not be used as the sole indicator of emotional and aesthetic responses (Subsection 3.4), that individual differences should be taken into account (Subsection 8.3), particularly because chills now appear to be a multi-faceted phenomenon (Subsection 2.4), which should be taken into consideration. We argued that a combination of self-reports and objective measures are best suited for the study of chills (Subsection 4.4), and that care should be taken when validating self-reports of chills with skin conductance response (Subsection 4.1). We highlighted that further study of physiological responses is needed to identify their precise time-course (Subsection 9.3) and the emotional specificity of chills (Subsection 5.4). More broadly, we believe causal approaches, naturalistic listening experiences, and longitudinal designs (Subsection 4.4) to be necessary to tease apart acoustic and musical elicitors (Subsection 7.2), to disentangle the psychological mechanisms which underlie chills (Subsection 7.4), and to identify the effects of familiarity (Subsection 7.5). Moreover, cross-cultural and developmental experiments are crucial to better understand the evolutionary causes of chills (Subsection 9.6). Finally, we have recommended the use of the terms *chills* and *piloerection* (Subsection 2.1), and suggest a definition for participants in research on chills, characterising chills as a fleeting, pleasurable bodily sensation, sometimes accompanied by goosebumps, experienced when listening to specific musical passages.

### 10.3 Dataset

With the aim of facilitating more integrated research on chills, we have compiled *Chills in Music (ChiM)*, a dataset which contains, to our knowledge, all pieces of music which have been reported to elicit chills in the literature reviewed in this article (https://doi.org/10.17605/osf.io/uyg7m).

## Acknowledgements

We thank Emmanouil Benetos and Ana Clemente for their valuable feedback on a previous version of this article.

## Funding source

This work was supported by the EPSRC and AHRC Centre for Doctoral Training in Media and Arts Technology [EP/L01632X/1].

## Declaration of interest

None.

## References


Altenmüller, E., Kopiez, R., & Grewe, O. (2013). A contribution to the evolutionary basis of music: Lessons from the chill response (E. Altenmüller, S. Schmidt, & E. Zimmermann, Eds.). In E. Altenmüller, S. Schmidt, & E. Zimmermann (Eds.), *Evolution of emotional communication: From sounds in nonhuman mammals to speech and music in man*. Oxford, UK, Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199583560.003.0019

Archie, P., Bruera, E., & Cohen, L. (2013). Music-based interventions in palliative cancer care: A review of quantitative studies and neurobiological literature. *Support. Care Cancer*, *21*, 2609–2624. https://doi.org/10.1007/s00520-013-1841-4

Balteș, R. F., Avram, J., Miclea, M., & Miu, A. C. (2011). Emotions induced by operatic music: Psychophysiological effects of music, plot, and acting: A scientist's tribute to Maria Callas. *Brain Cogn.*, *76*(1), 146–157. https://doi.org/10.1016/j.bandc.2011.01.012

Balteș, R. F., & Miu, A. C. (2014). Emotions during live music performance: Links with individual differences in empathy, visual imagery, and mood. *Psychomusicology Music Mind Brain*, *24*(1), 58–65. https://doi.org/10.1037/pmu0000030

Bannister, S. (2019). Distinct varieties of aesthetic chills in response to multimedia. *PLOS ONE*, *14*(11), e0224974. https://doi.org/10.1371/journal.pone.0224974

Bannister, S. (2020a). A survey into the experience of musically induced chills: Emotions, situations and music. *Psychol. Music*, *48*(2), 297–314. https://doi.org/10.1177/0305735618798024

Bannister, S. (2020b). A vigilance explanation of musical chills? Effects of loudness and brightness manipulations. *Music Sci.*, *3*, 1–17. https://doi.org/10.1177/2059204320915654

Bannister, S., & Eerola, T. (2018). Suppressing the chills: Effects of musical manipulation on the chills response. *Front. Psychol.*, *9*, 2046. https://doi.org/10.3389/fpsyg.2018.02046

Beier, E. J., Janata, P., Hulbert, J. C., & Ferreira, F. (2020). Do you chill when I chill? A cross-cultural study of strong emotional responses to music. *Psychol. Aesthet. Creat. Arts*, *Advance online publication*. https://doi.org/10.1037/aca0000310

Benedek, M., & Kaernbach, C. (2011). Physiological correlates and emotional specificity of human piloerection. *Biol. Psychol.*, *86*(3), 320–329. https://doi.org/10.1016/j.biopsycho.2010.12.012

Benedek, M., Wilfling, B., Lukas-Wolfbauer, R., Katzur, B. H., & Kaernbach, C. (2010). Objective and continuous measurement of piloerection. *Psychophysiology*, *47*(5), 989–993. https://doi.org/10.1111/j.1469-8986.2010.01003.x

Bharucha, J. J. (1994). Tonality and expectation (R. Aiello & J. A. Sloboda, Eds.). In R. Aiello & J. A. Sloboda (Eds.), *Musical perceptions*. New York, NY, Oxford University Press.

Bicknell, J. (2007). Explaining strong emotional responses to music: Sociality and intimacy. *J. Conscious. Stud.*, *14*(12), 5–23.

Blood, A. J., & Zatorre, R. J. (2001). Intensely pleasurable responses to music correlate with activity in brain regions implicated in reward and emotion. *Proc. Natl. Acad. Sci. U.S.A.*, *98*(20), 11818–11823. https://doi.org/10.1073/pnas.191355898

Branković, S. (2013). Neuroaesthetics and growing interest in "positive affect" in psychiatry: New evidence and prospects for the theory of informational needs. *Psychiatr. Danub.*, *25*(2), 97–107.

Brattico, E. (2019). The neuroaesthetics of music: A research agenda coming of age (M. H. Thaut & D. A. Hodges, Eds.). In M. H. Thaut & D. A. Hodges (Eds.), *The Oxford handbook of music and the brain*. Oxford, UK, Oxford University Press. https://doi.org/10.1093/oxfordhb/9780198804123.013.15

Brattico, E., Bogert, B., & Jacobsen, T. (2013). Toward a neural chronometry for the aesthetic experience of music. *Front. Psychol.*, *4*, 206. https://doi.org/10.3389/fpsyg.2013.00206

Brattico, E., Brattico, P., & Jacobsen, T. (2009). The origins of the aesthetic enjoyment of music — A review of the literature. *Music. Sci.*, *13*(Suppl. 2), 15–39. https://doi.org/10.1177/1029864909013002031

Brattico, E., & Pearce, M. T. (2013). The neuroaesthetics of music. *Psychol. Aesthet. Creat. Arts*, *7*(1), 48–61. https://doi.org/10.1037/a0031624

Brattico, E., & Varankaitė, U. (2019). Aesthetic empowerment through music. *Music. Sci.*, *23*(3), 285–303. https://doi.org/10.1177/1029864919850606

Carr, S. M., & Rickard, N. S. (2016). The use of emotionally arousing music to enhance memory for subsequently presented images. *Psychol. Music*, *44*(5), 1145–1157. https://doi.org/10.1177/0305735615613846

Chanda, M. L., & Levitin, D. J. (2013). The neurochemistry of music. *Trends Cogn. Sci.*, *17*(4), 179–193. https://doi.org/10.1016/j.tics.2013.02.007

Cheung, V. K. M., Harrison, P. M. C., Meyer, L., Pearce, M. T., Haynes, J.-D., & Koelsch, S. (2019). Uncertainty and surprise jointly predict musical pleasure and amygdala, hippocampus, and auditory cortex activity. *Curr. Biol.*, *29*(23), 4084–4092. https://doi.org/10.1016/j.cub.2019.09.067

Colver, M. C., & El-Alayli, A. (2016). Getting aesthetic chills from music: The connection between openness to experience and frisson. *Psychol. Music*, *44*(3), 413–427. https://doi.org/10.1177/0305735615572358

Corrigall, K. A., & Schellenberg, E. G. (2013). Music: The language of emotion (C. Mohiyeddini, M. Eysenck, & S. Bauer, Eds.). In C. Mohiyeddini, M. Eysenck, & S. Bauer (Eds.), *Handbook of psychology of emotions:*

*Recent theoretical perspectives and novel empirical findings*. Hauppauge, NY, Nova Science Publishers.

Corrigall, K. A., & Schellenberg, E. G. (2015). Liking music: Genres, contextual factors, and individual differences (J. P. Huston, M. Nadal, F. Mora, L. F. Agnati, & C. J. C. Conde, Eds.). In J. P. Huston, M. Nadal, F. Mora, L. F. Agnati, & C. J. C. Conde (Eds.), *Art, aesthetics, and the brain*. Oxford, UK, Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199670000.003.0013

Costa, P. T., & McCrae, R. R. (1992). *Revised NEO Personality Inventory (NEO-PI-R) and NEO Five-Factor Inventory (NEO-FFI) professional manual*. Odessa, FL, Psychological Assessment Resources.

Cotter, K. N., Prince, A. N., Christensen, A. P., & Silvia, P. J. (2019). Feeling like crying when listening to music: Exploring musical and contextual features. *Empir. Stud. Arts*, *37*(2), 119–137. https://doi.org/10.1177/0276237418805692

Cotter, K. N., Silvia, P. J., & Fayn, K. (2018). What does feeling like crying when listening to music feel like? *Psychol. Aesthet. Creat. Arts*, *12*(2), 216–227. https://doi.org/10.1037/aca0000108

Craig, D. G. (2005). An exploratory study of physiological changes during "chills" induced by music. *Music. Sci.*, *9*(2), 273–287. https://doi.org/10.1177/102986490500900207

Craig, D. G. (2009). Exploring music preference: Meaningfulness of music as a function of emotional reactions. *Nord. J. Music Ther.*, *18*(1), 57–69. https://doi.org/10.1080/08098130802697137

Dowd, E. C., & Barch, D. M. (2012). Pavlovian reward prediction and receipt in schizophrenia: Relationship to anhedonia. *PLOS ONE*, *7*(5), e35622. https://doi.org/10.1371/journal.pone.0035622

Dubé, L., & Le Bel, J. (2003). The content and structure of laypeople's concept of pleasure. *Cogn. Emot.*, *17*(2), 263–295. https://doi.org/10.1080/02699930302295

Eerola, T. (2018). Music and emotions (R. Bader, Ed.). In R. Bader (Ed.), *Springer handbook of systematic musicology*. Berlin, Germany, Springer. https://doi.org/10.1007/978-3-662-55004-5_29

Eerola, T., Vuoskoski, J. K., & Kautiainen, H. (2016). Being moved by unfamiliar sad music is associated with high empathy. *Front. Psychol.*, *7*, 1176. https://doi.org/10.3389/fpsyg.2016.01176

Egermann, H., Sutherland, M. E., Grewe, O., Nagel, F., Kopiez, R., & Altenmüller, E. (2011). Does music listening in a social context alter experience? A physiological and psychological perspective on emotion. *Music. Sci.*, *15*(3), 307–323. https://doi.org/10.1177/1029864911399497

Ferreri, L., Mas-Herrero, E., Zatorre, R. J., Ripollés, P., Gomez-Andres, A., Alicart, H., Olivé, G., Marco-Pallarés, J., Antonijoan, R. M., Valle, M., Riba, J., & Rodriguez-Fornells, A. (2019). Dopamine modulates the reward experiences elicited by music. *Proc. Natl. Acad. Sci. U.S.A.*, *116*(9), 3793–3798. https://doi.org/10.1073/pnas.1811878116

Fiske, A. P., Seibt, B., & Schubert, T. W. (2019). The sudden devotion emotion: Kama muta and the cultural practices whose function is to evoke it. *Emot. Rev.*, *11*(1), 74–86. https://doi.org/10.1177/1754073917723167

Fukui, H., & Toyoshima, K. (2013). Influence of music on steroid hormones and the relationship between receptor polymorphisms and musical ability: A pilot study. *Front. Psychol.*, *4*, 910. https://doi.org/10.3389/fpsyg.2013.00910

Fukui, H., & Toyoshima, K. (2014). Chill-inducing music enhances altruism in humans. *Front. Psychol.*, *5*, 1215. https://doi.org/10.3389/fpsyg.2014.01215

Fukushima, S., & Kajimoto, H. (2012). Facilitating a surprised feeling by artificial control of piloerection on the forearm (J.-M. Seigneur, Ed.). In J.-M. Seigneur (Ed.), *Proceedings of the 3rd Augmented Human International Conference, AH '12*, Megève, France, Association for Computing Machinery. https://doi.org/10.1145/2160125.2160133

Gabrielsson, A. (2001). Emotions in strong experiences with music (P. N. Juslin & J. A. Sloboda, Eds.). In P. N. Juslin & J. A. Sloboda (Eds.), *Music and emotion: Theory and research*. Oxford, UK, Oxford University Press.

Gabrielsson, A. (2011). *Strong experiences with music: Music is much more than just music*. Oxford, UK, Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199695225.001.0001

Gabrielsson, A., Whaley, J., & Sloboda, J. (2016). Peak experiences in music (S. Hallam, I. Cross, & M. Thaut, Eds.; 2nd). In S. Hallam, I. Cross, & M. Thaut (Eds.), *The Oxford handbook of music psychology* (2nd). Oxford, UK, Oxford University Press. https://doi.org/10.1093/oxfordhb/9780198722946.013.44

Gabrielsson, A., & Wik, S. L. (2003). Strong experiences related to music: A descriptive system. *Music. Sci.*, *7*(2), 157–217. https://doi.org/10.1177/102986490300700201

Gold, B. P., Pearce, M. T., Mas-Herrero, E., Dagher, A., & Zatorre, R. J. (2019). Predictability and uncertainty in the pleasure of music: A reward for learning? *J. Neurosci.*, *39*(47), 9397–9409. https://doi.org/10.1523/jneurosci.0428-19.2019

Goldstein, A. (1980). Thrills in response to music and other stimuli. *Physiol. Psychol.*, *8*(1), 126–129. https://doi.org/10.3758/bf03326460

Goodchild, M., Wild, J., & McAdams, S. (2019). Exploring emotional responses to orchestral gestures. *Music. Sci.*, *23*(1), 25–49. https://doi.org/10.1177/1029864917704033

Greasley, A., & Lamont, A. (2016). Musical preferences (S. Hallam, I. Cross, & M. Thaut, Eds.; 2nd). In S. Hallam, I. Cross, & M. Thaut (Eds.), *The Oxford handbook of music psychology* (2nd). Oxford, UK, Oxford University Press. https://doi.org/10.1093/oxfordhb/9780198722946.013.58

Grewe, O., Katzur, B., Kopiez, R., & Altenmüller, E. (2011). Chills in different sensory domains: Frisson elicited by acoustical, visual, tactile and gustatory stimuli. *Psychol. Music*, *39*(2), 220–239. https://doi.org/10.1177/0305735610362950

Grewe, O., Kopiez, R., & Altenmüller, E. (2009a). The chill parameter: Goose bumps and shivers as promising measures in emotion research. *Music Percept.*, *27*(1), 61–74. https://doi.org/10.1525/mp.2009.27.1.61

Grewe, O., Kopiez, R., & Altenmüller, E. (2009b). Chills as an indicator of individual emotional peaks. *Ann. N.Y. Acad. Sci.*, *1169*(1), 351–354. https://doi.org/10.1111/j.1749-6632.2009.04783.x

Grewe, O., Nagel, F., Kopiez, R., & Altenmüller, E. (2007). Listening to music as a re-creative process: Physiological, psychological, and psychoacoustical correlates of chills and strong emotions. *Music Percept.*, *24*(3), 297–314. https://doi.org/10.1525/mp.2007.24.3.297

Griffiths, T. D., Warren, J. D., Dean, J. L., & Howard, D. (2004). "When the feeling's gone": A selective loss of musical emotion. *J. Neurol. Neurosurg. Psychiatry*, *72*(2), 344–345. https://doi.org/10.1136/jnnp.2003.015586

Grunkina, V., Holtz, K., Klepzig, K., Neubert, J., Horn, U., Domin, M., Hamm, A. O., & Lotze, M. (2017). The role of left hemispheric structures for emotional processing as a monitor of bodily reaction and felt chill – A case-control functional imaging study. *Front. Hum. Neurosci.*, *10*, 670. https://doi.org/10.3389/fnhum.2016.00670

Guhn, M., Hamm, A., & Zentner, M. (2007). Physiological and musico-acoustic correlates of the chill response. *Music Percept.*, *24*(5), 473–483. https://doi.org/10.1525/mp.2007.24.5.473

Habibi, A., & Damasio, A. (2014). Music, feelings, and the human brain. *Psychomusicology Music Mind Brain*, *24*(1), 92–102. https://doi.org/10.1037/pmu0000033

Halpern, D. L., Blake, R., & Hillenbrand, J. (1986). Psychoacoustics of a chilling sound. *Percept. Psychophys.*, *39*(2), 77–80. https://doi.org/10.3758/bf03211488

Hanslick, E. (1854). *Vom Musikalisch-Schönen: Ein Beitrag zur Revision der ästhetik der Tonkunst*. Leipzig, Germany, Rudolph Weigel.

Hargreaves, D. J. (2012). Musical imagination: Perception and production, beauty and creativity. *Psychol. Music*, *40*(5), 539–557. https://doi.org/10.1177/0305735612444893

Hargreaves, D. J., & North, A. C. (2010). Experimental aesthetics and liking for music (P. N. Juslin & J. A. Sloboda, Eds.). In P. N. Juslin & J. A. Sloboda (Eds.), *Handbook of music and emotion: Theory, research, applications*. Oxford, UK, Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199230143.003.0019

Harrison, L., & Loui, P. (2014). Thrills, chills, frissons, and skin orgasms: Toward an integrative model of transcendent psychophysiological experiences in music. *Front. Psychol.*, *5*, 790. https://doi.org/10.3389/fpsyg.2014.00790

Harrison, N. R., & Clark, D. P. A. (2016). The observing facet of trait mindfulness predicts frequency of aesthetic experiences evoked by the arts. *Mindfulness*, *7*, 971–978. https://doi.org/10.1007/s12671-016-0536-6

Harvey, P.-O., Pruessner, J., Czechowska, Y., & Lepage, M. (2007). Individual differences in trait anhedonia: A structural and functional magnetic resonance imaging study in non-clinical subjects. *Mol. Psychiatry*, *12*, 767–775. https://doi.org/10.1038/sj.mp.4002021

Heathers, J. A. J., Fayn, K., Silvia, P. J., Tiliopoulos, N., & Goodwin, M. S. (2018). The voluntary control of piloerection. *PeerJ*, *6*, e5292. https://doi.org/10.7717/peerj.5292

Hernández, M., Palomar-García, M.-Á., Nohales-Nieto, B., Olcina-Sempere, G., Villar-Rodríguez, E., Pastor, R., Ávila, C., & Parcet, M.-A. (2019). Separate contribution of striatum volume and pitch discrimination to individual differences in music reward. *Psychol. Sci.*, *30*(9), 1352–1361. https://doi.org/10.1177/0956797619859339

Hodges, D. A. (2016). Bodily responses to music (S. Hallam, I. Cross, & M. Thaut, Eds.; 2nd). In S. Hallam, I. Cross, & M. Thaut (Eds.), *The Oxford handbook of music psychology* (2nd). Oxford, UK, Oxford University Press. https://doi.org/10.1093/oxfordhb/9780198722946.013.16

Hunter, P. G., & Schellenberg, E. G. (2010). Music and emotion (M. R. Jones, R. R. Fay, & A. N. Popper, Eds.). In M. R. Jones, R. R. Fay, & A. N. Popper (Eds.), *Music perception*. New York, NY, Springer. https://doi.org/10.1007/978-1-4419-6114-3_5

Huron, D. (2006). *Sweet anticipation: Music and the psychology of expectation*. Cambridge, MA, MIT Press.

Huron, D. (2016). Aesthetics (S. Hallam, I. Cross, & M. Thaut, Eds.; 2nd). In S. Hallam, I. Cross, & M. Thaut (Eds.), *The Oxford handbook of music psychology* (2nd). Oxford, UK, Oxford University Press. https://doi.org/10.1093/oxfordhb/9780198722946.013.19

Huron, D., & Margulis, E. H. (2010). Musical expectancy and thrills (P. N. Juslin & J. A. Sloboda, Eds.). In P. N. Juslin & J. A. Sloboda (Eds.), *Handbook of music and emotion: Theory, research, applications*. Oxford, UK, Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199230143.003.0021

Ishikawa, Y., Kawazoe, A., Chernyshov, G., Fujii, S., & Nakatani, M. (2019). The thermal feedback influencer: Wearable thermal display for enhancing the experience of music listening (H. Kajimoto, D. Lee, S.-Y. Kim, M. Konyo, & K.-U. Kyung, Eds.). In H. Kajimoto, D. Lee, S.-Y. Kim, M. Konyo, & K.-U. Kyung (Eds.), *Proceedings of the International AsiaHaptics Conference, AsiaHaptics 2018: Haptic interaction*, Songdo, Republic of Korea, Springer. https://doi.org/10.1007/978-981-13-3194-7_36

Jaimovich, J., Coghlan, N., & Knapp, R. B. (2013). Emotion in motion: A study of music and affective response (M. Aramaki, M. Barthet, R. Kronland-Martinet, & S. Ystad, Eds.). In M. Aramaki, M. Barthet, R. Kronland-Martinet, & S. Ystad (Eds.), *Proceedings of the 9th International Symposium on Computer Music Modeling and Retrieval, CMMR 2012: From sounds to music and emotions*, London, UK, Springer. https://doi.org/10.1007/978-3-642-41248-6_2

Juslin, P. N., Liljeström, S., Västfjäll, D., & Lundqvist, L.-O. (2010). How does music evoke emotions? (P. N. Juslin & J. A. Sloboda, Eds.). In P. N. Juslin & J. A. Sloboda (Eds.), *Handbook of music and emotion:*

*Theory, research, applications*. Oxford, UK, Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199230143.003.0022

Juslin, P. N. (2013). From everyday emotions to aesthetic emotions: Towards a unified theory of musical emotions. *Phys. Life Rev.*, *10*(3), 235–266. https://doi.org/10.1016/j.plrev.2013.05.008

Juslin, P. N. (2016). Emotional reactions to music (S. Hallam, I. Cross, & M. Thaut, Eds.; 2nd). In S. Hallam, I. Cross, & M. Thaut (Eds.), *The Oxford handbook of music psychology* (2nd). Oxford, UK, Oxford University Press. https://doi.org/10.1093/oxfordhb/9780198722946.013.17

Juslin, P. N. (2019). *Musical emotions explained*. Oxford, UK, Oxford University Press. https://doi.org/10.1093/oso/9780198753421.001.0001

Juslin, P. N., Harmat, L., & Eerola, T. (2014). What makes music emotionally significant? Exploring the underlying mechanisms. *Psychol. Music*, *42*(4), 599–623. https://doi.org/10.1177/0305735613484548

Juslin, P. N., & Västfjäll, D. (2008). Emotional responses to music: The need to consider underlying mechanisms. *Behav. Brain Sci.*, *31*(5), 559–575. https://doi.org/10.1017/s0140525x08005293

Kim, J., Seo, D. G., & Cho, Y.-H. (2014). A flexible skin piloerection monitoring sensor. *Appl. Phys. Lett.*, *104*, 253502. https://doi.org/10.1063/1.4881888

Klepzig, K., Horn, U., König, J., Holtz, K., Wendt, J., Hamm, A., & Lotze, M. (2020). Brain imaging of chill reactions to pleasant and unpleasant sounds. *Behav. Brain Res.*, *380*, 112417. https://doi.org/10.1016/j.bbr.2019.112417

Koelsch, S. (2010). Towards a neural basis of music-evoked emotions. *Trends Cogn. Sci.*, *14*(3), 131–137. https://doi.org/10.1016/j.tics.2010.01.002

Koelsch, S. (2014). Brain correlates of music-evoked emotions. *Nat. Rev. Neurosci.*, *15*, 170–180. https://doi.org/10.1038/nrn3666

Konečni, V. J. (2005). The aesthetic trinity: Awe, being moved, thrills. *Bull. Psychol. Arts*, *5*(2), 27–44. https://doi.org/10.1037/e674862010-005

Konečni, V. J. (2007). Music and emotion: An empirical critique of a key issue in the philosophy of music (A. Š. et al., Ed.). In A. Š. et al. (Ed.), *Proceedings of the 5th International Conference "Person – Color – Nature – Music"*, Daugavpils, Latvia, Daugavpils University.

Konečni, V. J. (2008). Does music induce emotion? A theoretical and methodological analysis. *Psychol. Aesthet. Creat. Arts*, *2*(2), 115–129. https://doi.org/10.1037/1931-3896.2.2.115

Konečni, V. J. (2013). Empirical psycho-aesthetics and her sisters: Substantive and methodological issues—Part II. *J. Aesthet. Educ.*, *47*(1), 1–21. https://doi.org/10.5406/jaesteduc.47.1.0001

Konečni, V. J., Wanic, R. A., & Brown, A. (2007). Emotional and aesthetic antecedents and consequences of music-induced thrills. *Am. J. Psychol.*, *120*(4), 619–643. https://doi.org/10.2307/20445428

Kreibig, S. D. (2010). Autonomic nervous system activity in emotion: A review. *Biol. Psychol.*, *84*(3), 394–421. https://doi.org/10.1016/j.biopsycho.2010.03.010

Laeng, B., Eidet, L. M., Sulutvedt, U., & Panksepp, J. (2016). Music chills: The eye pupil as a mirror to music's soul. *Conscious. Cogn.*, *44*, 161–178. https://doi.org/10.1016/j.concog.2016.07.009

Larsen, J. T., Berntson, G. G., Poehlmann, K. M., Ito, T. A., & Cacioppo, J. T. (2008). The psychophysiology of emotions (M. Lewis, J. M. Haviland-Jones, & L. F. Barrett, Eds.; 3rd). In M. Lewis, J. M. Haviland-Jones, & L. F. Barrett (Eds.), *Handbook of emotions* (3rd). New York, NY, Guilford Press.

Leder, H., Belke, B., Oeberst, A., & Augustin, D. (2004). A model of aesthetic appreciation and aesthetic judgments. *Br. J. Psychol.*, *94*(4), 489–508. https://doi.org/10.1348/0007126042369811

Leder, H., & Nadal, M. (2014). Ten years of a model of aesthetic appreciation and aesthetic judgments: The aesthetic episode – Developments and challenges in empirical aesthetics. *Br. J. Psychol.*, *105*(4), 443–464. https://doi.org/10.1111/bjop.12084

Levinson, J. (2006). Musical chills (J. Levinson, Ed.). In J. Levinson (Ed.), *Contemplating art: Essays in aesthetics*. Oxford, UK, Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199206179.003.0013

Levinson, J. (2009). The aesthetic appreciation of music. *Br. J. Aesthet.*, *49*(4), 415–425. https://doi.org/10.1093/aesthj/ayp043

Linnemann, A., Kreutz, G., Gollwitzer, M., & Nater, U. M. (2018). Validation of the German version of the Music-Empathizing-Music-Systemizing (MEMS) inventory (short version). *Front. Behav. Neurosci.*, *12*, 153. https://doi.org/10.3389/fnbeh.2018.00153

Logothetis, N. K. (2008). What we can do and what we cannot do with fMRI. *Nature*, *453*, 869–878. https://doi.org/10.1038/nature06976

Loui, P., Patterson, S., Sachs, M. E., Leung, Y., Zeng, T., & Przysinda, E. (2017). White matter correlates of musical anhedonia: Implications for evolution of music. *Front. Psychol.*, *8*, 1664. https://doi.org/10.3389/fpsyg.2017.01664

Mallik, A., Chanda, M. L., & Levitin, D. J. (2017). Anhedonia to music and mu-opioids: Evidence from the administration of naltrexone. *Sci. Rep.*, (7), 41952. https://doi.org/10.1038/srep41952

Maruskin, L. A., Thrash, T. M., & Elliot, A. J. (2012). The chills as a psychological construct: Content universe, factor structure, affective composition, elicitors, trait antecedents, and consequences. *J. Pers. Soc. Psychol.*, *103*(1), 135–157. https://doi.org/10.1037/a0028117

Mas-Herrero, E., Marco-Pallares, J., Lorenzo-Seva, U., Zatorre, R. J., & Rodriguez-Fornells, A. (2013). Individual differences in music reward experiences. *Music Percept.*, *31*(2), 118–138. https://doi.org/10.1525/mp.2013.31.2.118

Mas-Herrero, E., Zatorre, R. J., Rodriguez-Fornells, A., & Marco-Pallarés, J. (2014). Dissociation between musical and monetary reward responses in specific musical anhedonia. *Curr. Biol.*, *24*(6), 699–704. https://doi.org/10.1016/j.cub.2014.01.068

Mathis, W. S., & Han, X. (2017). The acute effect of pleasurable music on craving for alcohol: A pilot crossover study. *J. Psychiatr. Res.*, *90*, 143–147. https://doi.org/10.1016/j.jpsychires.2017.04.008

McCrae, R. R. (2007). Aesthetic chills as a universal marker of openness to experience. *Motiv. Emot.*, *31*(1), 5–11. https://doi.org/10.1007/s11031-007-9053-1

McDermott, J. H. (2012). Auditory preferences and aesthetics: Music, voices, and everyday sounds (R. J. Dolan & T. Sharot, Eds.). In R. J. Dolan & T. Sharot (Eds.), *Neuroscience of preference and choice: Cognitive and neural mechanisms*. San Diego, CA, Academic Press. https://doi.org/10.1016/b978-0-12-381431-9.00020-6

Mencke, I., Omigie, D., Wald-Fuhrmann, M., & Brattico, E. (2019). Atonal music: Can uncertainty lead to pleasure? *Front. Neurosci.*, *12*, 979. https://doi.org/10.3389/fnins.2018.00979

Menninghaus, W., Wagner, V., Hanich, J., Wassiliwizky, E., Kuehnast, M., & Jacobsen, T. (2015). Towards a psychological construct of being moved. *PLOS ONE*, *10*(6), e0128451. https://doi.org/10.1371/journal.pone.0128451

Meyer, L. B. (1956). *Emotion and meaning in music*. Chicago, IL, Chicago University Press. https://doi.org/10.7208/chicago/9780226521374.001.0001

Miranda, R. A., & Ullman, M. T. (2007). Double dissociation between rules and memory in music: An event-related potential study. *NeuroImage*, *38*(2), 331–345. https://doi.org/10.1016/j.neuroimage.2007.07.034

Mlejnek, R. (2013). Physically experienced reactions and music: A questionnaire study of musicians and non-musicians (G. Luck & O. Brabant, Eds.). In G. Luck & O. Brabant (Eds.), *Proceedings of the 3rd International Conference on Music and Emotion, ICME3*, Jyväskylä, Finland, University of Jyväskylä, Department of Music.

Mori, K., & Iwanaga, M. (2014). Resting physiological arousal is associated with the experience of music-induced chills. *Int. J. Psychophysiol.*, *93*(2), 220–226. https://doi.org/10.1016/j.ijpsycho.2014.05.001

Mori, K., & Iwanaga, M. (2015). General reward sensitivity predicts intensity of music-evoked chills. *Music Percept.*, *32*(5), 484–492. https://doi.org/10.1525/mp.2015.32.5.484

Mori, K., & Iwanaga, M. (2017). Two types of peak emotional responses to music: The psychophysiology of chills and tears. *Sci. Rep.*, *7*, 46063. https://doi.org/10.1038/srep46063

Müllensiefen, D., Gingras, B., Musil, J., & Stewart, L. (2014). The musicality of non-musicians: An index for assessing musical sophistication in the general population. *PLOS ONE*, *9*(2), e89642. https://doi.org/10.1371/journal.pone.0089642

Nagel, F., Kopiez, R., Grewe, O., & Altenmüller, E. (2007). EMuJoy: Software for continuous measurement of perceived emotions in music. *Behav. Res. Methods*, *39*(2), 283–290. https://doi.org/10.3758/bf03193159

Nagel, F., Kopiez, R., Grewe, O., & Altenmüller, E. (2008). Psychoacoustical correlates of musically induced chills. *Music. Sci.*, *12*(1), 101–113. https://doi.org/10.1177/102986490801200106

Nusbaum, E. C., & Silvia, P. J. (2011). Shivers and timbres: Personality and the experience of chills from music. *Soc. Psychol. Pers. Sci.*, *2*(2), 199–204. https://doi.org/10.1177/1948550610386810

Nusbaum, E. C., Silvia, P. J., Beaty, R. E., Burgin, C. J., Hodges, D. A., & Kwapil, T. R. (2014). Listening between the notes: Aesthetic chills in everyday music listening. *Psychol. Aesthet. Creat. Arts*, *8*(1), 104–109. https://doi.org/10.1037/a0034867

Nusbaum, E. C., Silvia, P. J., Beaty, R. E., Burgin, C. J., & Kwapil, T. R. (2015). Turn that racket down! Physical anhedonia and diminished pleasure from music. *Empir. Stud. Arts*, *33*(2), 228–243. https://doi.org/10.1177/0276237415597392

Orne, M. T. (1962). On the social psychology of the psychological experiment: With particular reference to demand characteristics and their implications. *Am. Psychol.*, *17*(11), 776–783. https://doi.org/10.1037/h0043424

Panksepp, J. (1995). The emotional sources of “chills” induced by music. *Music Percept.*, *13*(2), 171–207. https://doi.org/10.2307/40285693

Panksepp, J. (2009). The emotional antecedents to the evolution of music and language. *Music. Sci.*, *13*(Suppl. 2), 229–259. https://doi.org/10.1177/1029864909013002111

Panksepp, J., & Bernatzky, G. (2002). Emotional sounds and the brain: The neuro-affective foundations of musical appreciation. *Behav. Process.*, *60*(2), 133–155. https://doi.org/10.1016/s0376-6357(02)00080-3

Panzarella, R. (1980). The phenomology of aesthetic peak experiences. *J. Humanist. Psychol.*, *20*(1), 69–85. https://doi.org/10.1177/002216788002000105

Park, K. S., Hass, C. J., Fawver, B., Lee, H., & Janelle, C. M. (2019). Emotional states influence forward gait during music listening based on familiarity with music selections. *Hum. Mov. Sci.*, *66*, 53–62. https://doi.org/10.1016/j.humov.2019.03.004

Pearce, M. T. (2018). Statistical learning and probabilistic prediction in music cognition: Mechanisms of stylistic enculturation. *Ann. N.Y. Acad. Sci.*, *1423*(1), 378–395. https://doi.org/10.1111/nyas.13654

Pearce, M. T., & Wiggins, G. A. (2012). Auditory expectation: The information dynamics of music perception and cognition. *Top. Cogn. Sci.*, *4*(4), 625–652. https://doi.org/10.1111/j.1756-8765.2012.01214.x

Pelowski, M., Markey, P. S., Forster, M., Gerger, G., & Leder, H. (2017). Move me, astonish me... delight my eyes and brain: The Vienna Integrated Model of top-down and bottom-up processes in Art Perception (VIMAP) and corresponding affective, evaluative, and neurophysiological correlates. *Phys. Life Rev.*, *21*, 80–125. https://doi.org/10.1016/j.plrev.2017.02.003

Pelowski, M., Markey, P., & Leder, H. (2018). Chills, aesthetic experience, and new versus old knowledge — What do chills actually portend? Comment on “Physics of mind: Experimental confirmations of theoretical predictions" by Schoeller et al. *Phys. Life Rev.*, *25*, 83–87. https://doi.org/10.1016/j.plrev.2018.03.014

Poldrack, R. A. (2011). Inferring mental states from neuroimaging data: From reverse inference to large-scale decoding. *Neuron*, *72*(5), 692–697. https://doi.org/10.1016/j.neuron.2011.11.001

Quesnel, D., & Riecke, B. E. (2018). Are you awed yet? How virtual reality gives us awe and goose bumps. *Front. Psychol.*, *9*, 2158. https://doi.org/10.3389/fpsyg.2018.02158

Rickard, N. S. (2004). Intense emotional responses to music: A test of the physiological arousal hypothesis. *Psychol. Music*, *32*(4), 371–388. https://doi.org/10.1177/0305735604046096

Sachs, M. E., Ellis, R. J., Schlaug, G., & Loui, P. (2016). Brain connectivity reflects human aesthetic responses to music. *Soc. Cogn. Affect. Neurosci.*, *11*(6), 884–891. https://doi.org/10.1093/scan/nsw009

Saffran, J. R., Johnson, E. K., Aslin, R. N., & Newport, E. L. (1999). Statistical learning of tone sequences by human infants and adults. *Cognition*, *70*(1), 27–52. https://doi.org/10.1016/s0010-0277(98)00075-4

Salimpoor, V. N., Benovoy, M., Larcher, K., Dagher, A., & Zatorre, R. J. (2011). Anatomically distinct dopamine release during anticipation and experience of peak emotion to music. *Nat. Neurosci.*, *14*(2), 257–262. https://doi.org/10.1038/nn.2726

Salimpoor, V. N., Benovoy, M., Longo, G., Cooperstock, J. R., & Zatorre, R. J. (2009). The rewarding aspects of music listening are related to degree of emotional arousal. *PLOS ONE*, *4*(10), e7487. https://doi.org/10.1371/journal.pone.0007487

Salimpoor, V. N., Zald, D. H., Zatorre, R. J., Dagher, A., & McIntosh, A. R. (2015). Predictions and the brain: How musical sounds become rewarding. *Trends Cogn. Sci.*, *19*(2), 86–91. https://doi.org/10.1016/j.tics.2014.12.001

Salimpoor, V. N., & Zatorre, R. J. (2013). Neural interactions that give rise to musical pleasure. *Psychol. Aesthet. Creat. Arts*, *7*(1), 62–75. https://doi.org/10.1037/a0031819

Schaefer, H.-E. (2017). Music-evoked emotions—Current studies. *Front. Neurosci.*, *11*, 600. https://doi.org/10.3389/fnins.2017.00600

Schäfer, T., & Sedlmeier, P. (2010). What makes us like music? Determinants of music preference. *Psychol. Aesthet. Creat. Arts*, *4*(4), 223–234. https://doi.org/10.1037/a0018374

Schäfer, T., & Sedlmeier, P. (2011). Does the body move the soul? The impact of arousal on music preference. *Music Percept.*, (29), 37–50. https://doi.org/10.1525/mp.2011.29.1.37

Scherer, K. R. (2009). The dynamic architecture of emotion: Evidence for the component process model. *Cogn. Emot.*, *23*(7), 1307–1351. https://doi.org/10.1080/02699930902928969

Scherer, K. R., Zentner, M. R., & Schacht, A. (2001). Emotional states generated by music: An exploratory study of music experts. *Music. Sci.*, *5*(Suppl. 1), 149–171. https://doi.org/10.1177/10298649020050s106

Schoeller, F. (2015). Knowledge, curiosity, and aesthetic chills. *Front. Psychol.*, *6*, 1546. https://doi.org/10.3389/fpsyg.2015.01546

Schoeller, F., Eskinazi, M., & Garreau, D. (2018). Dynamics of the knowledge instinct: Effects of incoherence on the cognitive system. *Cogn. Syst. Res.*, *48*, 85–91. https://doi.org/10.1016/j.cogsys.2017.07.005

Schoeller, F., & Perlovsky, L. (2016). Aesthetic chills: Knowledge-acquisition, meaning-making, and aesthetic emotions. *Front. Psychol.*, *7*, 1093. https://doi.org/10.3389/fpsyg.2016.01093

Schoeller, F., Perlovsky, L., & Arseniev, D. (2018). Physics of mind: Experimental confirmations of theoretical predictions. *Phys. Life Rev.*, *25*, 45–68. https://doi.org/10.1016/j.plrev.2017.11.021

Schubert, E. (2013). Emotion felt by the listener and expressed by the music: Literature review and theoretical perspectives. *Front. Psychol.*, *4*, 837. https://doi.org/10.3389/fpsyg.2013.00837

Schubert, E., North, A. C., & Hargreaves, D. J. (2016). Aesthetic experience explained by the affect-space framework. *Empir. Music. Rev.*, *11*(3–4), 330–345. https://doi.org/10.18061/emr.v11i3-4.5115

Schubert, T. W., Zickfeld, J. H., Seibt, B., & Fiske, A. P. (2018). Moment-to-moment changes in feeling moved match changes in closeness, tears, goosebumps, and warmth: Time series analyses. *Cogn. Emot.*, *32*(1), 174–184. https://doi.org/10.1080/02699931.2016.1268998

Schurtz, D. R., Blincoe, S., Smith, R. H., Powell, C. A. J., Combs, D. J. Y., & Kim, S. H. (2012). Exploring the social aspects of goose bumps and their role in awe and envy. *Motiv. Emot.*, *36*, 205–217. https://doi.org/10.1007/s11031-011-9243-8

Seibt, B., Schubert, T. W., Zickfeld, J. H., & Fiske, A. P. (2017). Interpersonal closeness and morality predict feelings of being moved. *Emotion*, *17*(3), 389–394. https://doi.org/10.1037/emo0000271

Seibt, B., Schubert, T. W., Zickfeld, J. H., Zhu, L., Arriaga, P., Simão, C., Nussinson, R., & Fiske, A. P. (2018). Kama muta: Similar emotional responses to touching videos across the United States, Norway, China, Israel, and Portugal. *J. Cross-Cult. Psychol.*, *49*(3), 418–435. https://doi.org/10.1177/0022022117746240

Silvia, P. J., Fayn, K., Nusbaum, E. C., & Beaty, R. E. (2015). Openness to experience and awe in response to nature and music: Personality and profound aesthetic experiences. *Psychol. Aesthet. Creat. Arts*, *9*(4), 376–384. https://doi.org/10.1037/aca0000028

Silvia, P. J., & Nusbaum, E. C. (2011). On personality and piloerection: Individual differences in aesthetic chills and other unusual aesthetic experiences. *Psychol. Aesthet. Creat. Arts*, *5*(3), 208–214. https://doi.org/10.1037/a0021914

Sloboda, J. A. (1991). Music structure and emotional response: Some empirical findings. *Psychol. Music*, *19*(2), 110–120. https://doi.org/10.1177/0305735691192002

Solberg, R. T., & Dibben, N. (2019). Peak experiences with electronic dance music: Subjective experiences, physiological responses, and musical characteristics of the break routine. *Music Percept.*, *36*(4), 371–389. https://doi.org/10.1525/mp.2019.36.4.371

Starcke, K., von Georgi, R., Tiihonen, T. M., Laczika, K.-F., & Reuter, C. (2019). Don't drink and chill: Effects of alcohol on subjective and physiological reactions during music listening and their relationships with personality and listening habits. *Int. J. Psychophysiol.*, *142*, 25–32. https://doi.org/10.1016/j.ijpsycho.2019.06.001

Steinbeis, N., Koelsch, S., & Sloboda, J. A. (2006). The role of harmonic expectancy violations in musical emotions: Evidence from subjective, physiological, and neural responses. *J. Cogn. Neurosci.*, *18*(8), 1380–1393. https://doi.org/10.1162/jocn.2006.18.8.1380

Strick, M., de Bruin, H. L., de Ruiter, L. C., & Jonkers, W. (2015). Striking the right chord: Moving music increases psychological transportation and behavioral intentions. *J. Exp. Psychol. Appl.*, *21*(1), 57–72. https://doi.org/10.1037/xap0000034

Sumpf, M., Jentschke, S., & Koelsch, S. (2015). Effects of aesthetic chills on a cardiac signature of emotionality. *PLOS ONE*, *10*(6), e0130117. https://doi.org/10.1371/journal.pone.0130117

Sutherland, M. E., Grewe, O., Egermann, H., Nagel, F., Kopiez, R., & Altenmüller, E. (2009). The influence of social situations on music listening. *Ann. N.Y. Acad. Sci.*, *1169*, 363–367. https://doi.org/10.1111/j.1749-6632.2009.04764.x

Verhaeghen, P. (2018). Once more, with feeling: The role of familiarity in the aesthetic response. *Psychol. Rec.*, *68*, 379–384. https://doi.org/10.1007/s40732-018-0312-1

Vuoskoski, J. K., & Eerola, T. (2017). The pleasure evoked by sad music is mediated by feelings of being moved. *Front. Psychol.*, *8*, 439. https://doi.org/10.3389/fpsyg.2017.00439

Vuust, P., & Kringelbach, M. L. (2010). The pleasure of music (M. L. Kringelbach & K. C. Berridge, Eds.). In M. L. Kringelbach & K. C. Berridge (Eds.), *Pleasures of the brain*. Oxford, UK, Oxford University Press.

Wassiliwizky, E., Jacobsen, T., Heinrich, J., Schneiderbauer, M., & Menninghaus, W. (2017). Tears falling on goosebumps: Co-occurence of lacrimation and emotional piloerection indicates a psychophysiological climax in emotional arousal. *Front. Psychol.*, *8*, 41. https://doi.org/10.3389/fpsyg.2017.00041

Wassiliwizky, E., Koelsch, S., Wagner, V., Jacobsen, T., & Menninghaus, W. (2017). The emotional power of poetry: Neural circuitry, psychophysiology and compositional principles. *Soc. Cogn. Affect. Neurosci.*, *12*(8), 1129–1240. https://doi.org/10.1093/scan/nsx069

Wassiliwizky, E., Wagner, V., Jacobsen, T., & Menninghaus, W. (2015). Art-elicited chills indicate states of being moved. *Psychol. Aesthet. Creat. Arts*, *9*(4), 405–416. https://doi.org/10.1037/aca0000023

Weth, K., Raab, M. H., & Carbon, C.-C. (2015). Investigating emotional responses to self-selected sad music via self-report and automated fa-

cial analysis. *Music. Sci.*, *19*(4), 412–432. https://doi.org/10.1177/1029864915606796
Zatorre, R. J. (2003). Music and the brain. *Ann. N.Y. Acad. Sci.*, *999*(1), 4–14. https://doi.org/10.1196/annals.1284.001
Zatorre, R. J. (2015). Musical pleasure and reward: Mechanisms and dysfunction. *Ann. N.Y. Acad. Sci.*, *1337*(1), 202–211. https://doi.org/10.1111/nyas.12677
Zatorre, R. J., & Salimpoor, V. N. (2013). From perception to pleasure: Music and its neural substrates. *Proc. Natl. Acad. Sci. U.S.A.*, *110*(Suppl. 2), 10430–10437. https://doi.org/10.1073/pnas.1301228110
Zentner, M., & Eerola, T. (2010). Self-report measures and models (P. N. Juslin & J. A. Sloboda, Eds.). In P. N. Juslin & J. A. Sloboda (Eds.), *Handbook of music and emotion: Theory, research, applications*. Oxford, UK, Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199230143.003.0008
Zentner, M., Grandjean, D., & Scherer, K. R. (2008). Emotions evoked by the sound of music: Characterization, classification, and measurement. *Emotion*, *8*(4), 494–521. https://doi.org/10.1037/1528-3542.8.4.494
Zickfeld, J. H., Schubert, T. W., Seibt, B., Blomster, J. K., Arriaga, P., Basabe, N., Blaut, A., Caballero, A., Carrera, P., Dalğar, I., Ding, Y., Dumont, K., Gaulhofer, V., Gračanin, A., Gyenis, R., Hu, C.-P., Kardum, I., Lazarević, L., Mathew, L., … Fiske, A. P. (2019). Kama muta: Conceptualizing and measuring the experience often labelled being moved across 19 nations and 15 languages. *Emotion*, *19*(3), 402–424. https://doi.org/10.1037/emo0000450
Zickfeld, J. H., Schubert, T. W., Seibt, B., & Fiske, A. P. (2017). Empathic concern is part of a more general communal emotion. *Front. Psychol.*, *8*, 723. https://doi.org/10.3389/fpsyg.2017.00723
Zickfeld, J. H., Schubert, T. W., Seibt, B., & Fiske, A. P. (2019). Moving through the literature: What is the emotion often denoted being moved? *Emot. Rev.*, *11*(2), 123–139. https://doi.org/10.1177/1754073918820126