A model of time-varying music engagement

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Abstract

The current paper offers a model of time-varying music engagement, defined as changes in curiosity, attention and positive valence, as music unfolds over time. First, we present research (including new data) showing that listeners tend to allocate attention to music in a manner that is guided by both features of the music and listeners' individual differences. Next, we review relevant predictive processing literature before using this body of work to inform our model. In brief, we propose that music engagement, over the course of an extended listening episode, may constitute several cycles of curiosity, attention and positive valence that are interspersed with moments of mind-wandering. Further, we suggest that refocussing on music after an episode of mind-wandering can be due to triggers in the music or, conversely, mental action that occurs when the listener realizes they are mind-wandering. Finally, we argue that factors that modulate both overall levels of engagement and how it changes over time include music complexity, listener background and the listening context. Our paper highlights how music can be used to provide insights into the temporal dynamics of attention and into how curiosity might emerge in everyday contexts.

Keywords: Music engagement, Curiosity, Attention, Valence, Predictive processing

Over the course of a music listening experience, an individual may find their focus switching between the music and other thoughts or actions. However, a theoretical model of the psychological processes and factors determining the level and dynamics of engagement with music over extended periods of time remains absent. This gap limits opportunities to leverage on music listening as a rich, complex and ubiquitous activity: one that can provide insights into the temporal dynamics of attention, and illuminate how states like curiosity and mind-wandering emerge in everyday contexts.

In the last decades, the predictive processing (PP) framework has been widely adopted in research on music listening [1,2]. According to the PP framework, prediction errors arise from mismatches between incoming sensory input and an organism's internal model. These prediction errors are then used to both update the model – so that it becomes more accurate – and to resample the world, so as to optimally guide future predictions. A growing body of work has provided physiological evidence for these predictive mechanisms, in general [3–6], and in the context of music listening [7–10] and has clarified their relationship with other psychological phenomena such as curiosity, attention, and valence. However, despite its relevance, the PP literature on curiosity, attention and valence has not yet been substantially used to account for naturalistic music listening experiences.

Here we show how this PP literature can help inform a model of the music listening experience on a longer timescale than has previously been attempted (but see [11]). First, we review current operationalisations of music engagement, before then showing how experimental studies and corpus analyses point to the role of music acoustic and structural features in driving it. After presenting empirical data (published and new) on the role and nature of curiosity, attention and positive valence during music listening, we provide a brief overview of PP accounts of the three psychological constructs. Finally, we present our integrative model for exploring time-varying music engagement and discuss some implications and directions for future research.

1. Operationalizing time-varying music engagement

The Oxford learners' dictionary describes "engagement" as being involved with [someone or] something in order to understand them/it. In psychology, engagement has variously been described as the connection between person and activity [12], as reflecting a person's active involvement in a task [13] and as a sort of motivated state that involves cognitive, behavioural and affective elements [13,14].

In the music psychology literature, "engagement" is used to imply at least two meanings. On the one hand, music engagement is taken to mean participation in a variety of music-related activities from musical practice and performance to attending concerts [15,16]. On the other hand, *time-varying* music engagement, which is associated with discrete listening episodes, has been described as "how engaging listeners find a piece of music throughout the continuous listening process" [17].

With respect to this latter understanding of the term, music engagement has also been defined as being "actively immersed in the experience of listening to music, to the exclusion of extra-musical stimuli" [18,19] while another operationalization that has found significant resonance [14,17,20,21] describes it as being "compelled, drawn in, connected to what is happening in the music, interested in what will happen next." [22]. Finally, in yet other conceptualizations, music engagement, along with other forms of engagement (e.g., engagement with narratives) has been defined as "emotionally laden attention" [20,23,24] and as a brain state associated with "increased affect, attention, and memory recall" [25].

Worth noting is that, across several accounts, time-varying music engagement is described as multidimensional, multifaceted and strongly dependent on several factors including the individual, the musical style, and culturally-determined referential frameworks [18,20,26,27]. However, perhaps the most striking commonality across current operationalisations is the idea that time-varying music engagement (music engagement, henceforth) involves not just heightened attention but also heightened affect; the latter particularly in the form of curiosity and interest.

2. Empirical Literature

2.1 Behavioural and neuroscientific studies on music engagement

Studies on music engagement suggest that dynamics and melody are prominent aspects of the listener's conscious experience of music [28–30], and that novelty and change, in general (e.g., in volume, tempo, instrumentation, or entry of vocals), are particularly effective in (re)orienting listeners' attention to music when they are carrying out concurrent tasks [31,32]. The importance of novelty and change in engaging listeners is supported by findings that the degree to which the entry of instruments is staggered influences how long listeners engage with musical excerpts [33]. Similarly, the seeming importance of melody and dynamics in music engagement is corroborated by studies that require participants to continuously rate their experience of heard music (e.g., [34–36]).

Since much music is often structured to afford changes in expectations over time [37–39], it is relevant to highlight studies that demonstrate an influence of information theoretic principles on music engagement. For instance, some degree of complexity has been shown to increase the amount of time listeners engage with a musical stimulus [40] with recent work suggesting that such engagement-enhancing effects of complexity are linked to higher-order feelings of interest and enjoyment [33]. Further, speaking to a potentially important relationship between music engagement and positive affect, continuous ratings of musical engagement have been shown to significantly predict the reported valence of a piece [17]. According to the authors, musical engagement "likely mediates the relationship between acoustic parameters in music and listeners' affective responses" [17].

While enlightening, a concern of existing behavioural research on music engagement is that requiring participants to provide continuous reports of their levels of engagement may change the listening experience itself. Here, a rising interest in increasing the ecological validity of neuroscientific research, by using more complex and realistic stimuli, holds promise for research into music engagement. In a growing body of work, engagement is held to be reflected in the degree of inter-subject correlation (ISC; for a review of ISC see [41]) seen in neural signals while participants engage with a continuous naturalistic stimulus ([23,24,42,43]). Indeed ISC – the degree to which continuous responses synchronize across subjects – has been estimated and interpreted in the context of a variety of stimuli including movies [24,44,45], auditory narratives [23,46] and, most relevantly here, music [20,25,42,43,47].

In the context of music listening, it has been pointed out that neural synchronization tends to be high during salient moments that are associated with unexpected events [42]. Indeed, it would seem that a key driver of ISC is contrastive change particularly with respect to acoustic features [20,42,43,48]: In one study highlighting the role of contrastive change, peripheral-physiology data collected in a live concert setting showed highest synchrony levels at phrase boundaries [49].

However, complementary to such findings (that emphasise low-level triggers of ISC) are others highlighting the wide range of factors that seem to influence it. For instance, it has been shown that minimalist pieces featuring a high degree of repetition result in lower ISC values [20], and that ISC tends to decrease over repeated exposures to the same music [24,25,43]. Interestingly, Madsen and colleagues [43] found, however, that ISC was modulated by an interaction between repeated exposure and familiarity whereby, while ISC decreased when familiar music was repeated, ISC was sustained, at least for musically-trained participants, when the music repeated was unfamiliar.

Such results suggest that ISC tracks more than just acoustic features, and are in line with the idea that expert listeners are more equipped to learn the regularities in auditory stimuli than non-expert listeners are [50]. They also raise the possibility that ISC may be tracking a psychological process somewhat akin to attention. Here, given that operationalisations of music engagement directly associate it with attention, it is relevant to highlight that studies have linked ISC increases with increases in top-down attentional states [43,51]. Similarly, with operationalisations of music engagement associating it with emotion, it is noteworthy that moments of high tension and suspense tend to elicit high ISC [24,52], with one study reported increasing ISC particularly in the build-up to "climactic highpoints'' [42].

As the above literature would seem to suggest that ISC is a useful index of time-varying music engagement, it is important to emphasise its limitations. Indeed, in being defined by synchrony across participants, ISC can only provide a measure of engagement that is "shared" across participants. In other words, while ISC reveals where all or most listeners might be engaging with ongoing musical materials, this index cannot (in its basic form) capture where listeners show differences in engagement[1].

Nevertheless, taken together, the empirical literature that evaluates subjective reports, and ISC of signals, suggests that certain music features may be able to drive (shared) engagement while other features may tend to reduce it. Further, it shows that while contrastive change appears to be a key trigger of ISC, ISC is nevertheless more than just passive neural tracking of abrupt changes in acoustic features. Here, however, not least given the limitations of the above approaches, an important question is whether music compositional practices can be said to corroborate such empirical findings. Fortunately, with the many draws on attention in today's world – which make it increasingly difficult to capture and maintain a person's engagement for extended periods of time [53] - such questions are increasingly being asked in the wider research community.

2.2 Corpus analysis studies

The term *Attention economy* emerged in the 1970s [53] to describe the idea that attention is a limited resource that must be distributed between different information

[1] Here we speculate on two ways in which this limitation can be mitigated. Firstly, studies could compute ISC from several listening episodes of a given individual, or secondly, ISC could be computed from small subsamples of listeners that share relevant traits or experiences (as carried out to some extent by Madsen and colleagues [43]). However, it is important to note that the former approach would suffer from the effect of repeated listenings, while the latter would likely suffer from considerable noise, given the challenge in specifying how any particular participant may be expected to respond to music.

sources. Since then, the idea of an economy of attention has been propagated extensively [54–56], including in the context of music listening [57] .

Explicitly operationalising attention economy principles as those favoring focused mental engagement with a specific information generator, Gauvin [57] asked whether they can be used to account for the evolution of music compositional practices in recent decades. Interestingly, by analysing approximately 300 popular songs between 1986 and 2015, this author was able to show changes in practice that are consistent with a number of such principles. Specifically, they were able to show that, over the decades, not only have instrumental introductions shortened from approximately 23 to five seconds but relatedly, first instantiations of vocals and the hook (highly attention-grabbing parts of music) in music also seem to enter increasingly earlier.

Yet other studies suggest that musicians and producers may have been adapting their practices to make music more attention-grabbing. For example, estimating perceived loudness for half a million popular recordings between 1955 and 2010, Serrà and colleagues [58] showed, in line with evidence that loudness is a key driver of engagement [30], that this aspect of music has tended to increase over time. Further, in addition to demonstrations that the majority of popular songs feature surprising harmonic events [59], there is evidence that they have become increasingly faster since the 1990s ([57], but see [60]).

Taken together, current operationalisations suggest that interest, curiosity and attention are key to what it means to be engaged with a musical stimulus, while experimental data and corpus analysis studies are revealing key features that may drive engagement with music. In the next section, we show how recent studies exploring curiosity and attention in the context of music listening provide support for a number of key ideas proposed in our model; namely that music tends to capture (and sustain) curiosity (and attention) as a function of musical features, style and individual listeners' characteristics.

2.3 Behavioural studies on curiosity during music listening

Since a listener's engagement with a piece of music often wanes substantially within the music's first few seconds [61], it follows that events that induce curiosity, and (re-) command attention towards music are needed to keep listeners engaging over extended periods of time. However, despite the relatively widespread idea that curiosity and attention may be important components of music engagement, there has been little direct empirical research on the topic.

Indeed, in perhaps the first empirical study to examine curiosity in the context of music listening, Omigie and Ricci [62] investigated the extent to which listeners' perception of change in music triggered their curiosity as to how the music would unfold. Specifically, participants provided continuous ratings of their subjective experience of curiosity, change and arousal, in response to unfamiliar musical excerpts. Using granger causality, a statistical technique that helps determine whether one time-series is useful in forecasting another, the authors found that for all musical pieces, the perceptual experience of change seemed to precede and statistically "cause" feelings of curiosity.

Complementing this evidence of a role of change in driving engagement, a further study from the same authors asked whether music's information theoretic properties can be seen to influence how curiosity is experienced during listening [63]. Specifically, listeners indicated, when cued, how curious they were as to how melodies presented to them would continue. Crucially, thanks to use of a statistical model of melodic expectancy [64] to estimate the information content (IC; unexpectedness) and entropy (uncertainty) of individual melodic notes, Omigie & Ricci [63] were able to demonstrate a positive association between curiosity and note IC in low entropy contexts, that was less evident in high entropy contexts. Indeed, in those high entropy contexts, low IC was seen to sometimes be associated with greater curiosity.

Critically, such findings are in line with the PP framework which emphasises that curiosity is experienced in situations where epistemic learning seems to be afforded (Section 3.2). The findings of an interaction between IC and entropy in accounting for curiosity [63] are also compelling given reports of a similar interaction between IC and entropy for musical pleasure [65,66]. However, the paper from Omigie & Ricci [63] can be considered particularly helpful in showing how individual differences may influence the unfolding of both curiosity and appreciation during music listening. Specifically, not only was it able to show that expert listeners' curiosity ratings tended to be more strongly influenced by musical structure, it also revealed that listeners with differing curiosity profiles differed in their relative enjoyment of high and low IC musical events; this in line with findings about how trait curiosity influences appreciation of unfamiliar music [67].

2.4 Using atonal music to explore the factors influencing attentional engagement

Having presented evidence that feelings of curiosity during music listening seem to emerge in ways that are in line with general principles, we use the current section to present new data on some of the factors influencing attentional engagement. In contrast to previous work (in general and reviewed here) that has tended to use (Western) music characterised by tonal and metrical hierarchies (tonal music), the current study uses atonal music, a style of Western art music that was prominent in the beginning of the 21st century and which is often characterised by an absence of such regularities.

Atonal music, in being very complex and unfamiliar to all but a small group of listeners, affords the opportunity to examine how factors like style complexity and expertise levels seem to influence engagement. Thus, in a large-scale study, we collected brain and behavioural data from 20 non-musicians (NM), 19 musicians specialized in classic-romantic repertoire (CM) and 19 musicians specialized in Western art music from the 20th/21st century (CCM; i.e. contemporary classical music, which includes atonal music). Prior to the study, all participants provided written consent and the study was approved by the local ethics committee of the University Hospital Frankfurt (reference number 415/17). Over the course of the study, participants were presented with 20 tonal (low uncertainty) and 20 atonal (high uncertainty) piano music excerpts lasting 45 seconds on average and after each excerpt indicated on a 6-point Likert scale ('Strongly agree' to 'Strongly disagree') how well they were able to follow each of the musical excerpts (specifically the level of their agreement with the statement "I could follow the music well": Figure 1A). With our analysis, we interrogated the extent to which listeners' ability to follow the music (i.e., deploy top-down attention on the heard music) was influenced by the style of music and listeners' expertise (Figure 1B and below).

We invite the reader to find more detail on methods and results in supplementary materials. However, in brief, following an initial linear mixed model that showed main effects of musical style (F (1, 38.01) = 170.98, p < 0.001), a main effect of expertise (F (2, 55.01) = 13.19, p < 0.001) and an interaction between the two (F (2, 2217.06) = 25.57, p < 0.001), we carried out three follow-up models that compared two expertise groups at a time. These models showed that all listeners found it more difficult to deploy top-down attention to atonal than to tonal music and that NM were generally poorer than both expert groups for both styles of music.

Interestingly, results also demonstrated that while the two expert groups did not differ in overall ability ($B = 0.36$, $SE = 0.25$, $df = 38.40$, $t = 1.43$, $p = 0.16$), the CCM group nevertheless differed from both NM and CM, with respect to ability to deploy attention to atonal as compared to tonal music ($B = 1.04$, $SE = 0.08$, $df = 85.17$, $t = 13.26$, $p < 0.01$). Specifically, compared to the two groups with no expertise in atonal music, the difference between ability to deploy attention to atonal and tonal music was significantly smaller in the CCM group. Comparing the CCM to CM (who did not differ in general ability to deploy attention to both musical styles), CCM demonstrated a numerical tendency to be, on the one hand, better than CM at following the atonal music but, on the other hand, worse than CM at following the tonal music.

Our data are interesting in highlighting the difficulty of engaging with atonal music even for those that have specific expertise in it. Indeed, our findings add support to our proposal that this kind of music be adopted in research in order to help understand the musical aesthetic experience in all its variety [68]. More pertinently, however, by suggesting that expertise in a complex music style may lead to both a greater ability to engage with complex music, and a reduced ability, or desire, to engage with less-complex musical styles, our data show how different factors can interact to guide levels of music engagement.

Taken together, our review of old and new data demonstrates how listeners show curiosity and allocate attention to music in a manner that is guided by both features of the music and listeners' individual differences. However, it is clear that the absence of a theoretical framework that is able to guide research on music engagement has limited both the extent to which existing findings can be confidently interpreted, and the extent to which insights can be used more broadly. In the following section, we review how curiosity, attention and valence is accounted for within the PP framework, allowing us to later use these insights to inform our model of musical engagement.

INSERT FIGURE 1 ABOUT HERE.

3. Curiosity, attention and valence in the PP framework

3.1 Predictive coding and active inference

The PP framework can be seen as an application of the free energy principle [69,70] which posits that living creatures must minimise free energy. Within this principle, free energy corresponds to a quantification of the divergence between observed and expected data, given an agent's generative model. Critically, the PP framework comprises both predictive coding – the idea that when sensory input is inconsistent with an agent's generative model, prediction errors propagate in order to change said generative model – and active inference– the idea that the organism will sample the environment (take action) in a way that maximises evidence for its model.

In active inference, in general, an agent uses its generative model to infer the most likely causes of observable outcomes; where a generative model is simply a probabilistic specification of how outcomes follow on from states (causes). In the special case of *deep* or hierarchical active inference, however, state transitions take on a nested temporal structure, whereby higher levels evolve at a slower time scale than that of the level below. One benefit of such deep models is that agents - in the process of inferring causes of outcomes - are able to build evidence over different time scales.

Deep generative models have been used to account for complex psychological processes like working memory and reading [71,72]. In the context of reading, an agent with a deep model can keep in mind those words or letters that are likely to be sampled in the future; allowing it to skip words and still comprehend the sentence. Recently, it has been suggested that having a deep generative model allows agents to access and control aspects of the self [73]. Indeed, it is against this backdrop that deep active inference is increasingly being used to account for attentional control, meta-awareness and affective states.

In the following review of the PP literature, we show how curiosity as an experience emerges from an exposure to novel combinations of hidden states and outcomes. We then show how attention, meta-awareness and mental action are made possible by agents having higher levels in their (deep) generative models that make lower levels visible and therefore controllable. Finally, we show how, according to the PP framework, positive valence can be explained by the rate of prediction error reduction. In the section that follows our PP review, we outline how and why all three processes are intrinsic to the phenomenon that is music engagement.

3.2. Accounting for curiosity

Extending earlier work on perception, the PP framework is increasingly being used to provide formal accounts of epistemic emotions like curiosity and insight [71,74,75]. Critically, by showing how curiosity can be accommodated within the same imperative (namely free energy minimisation) as other relevant phenomena (such as attention and emotion), such work provides a promising starting point for developing a PP account of music engagement.

PP accounts of curiosity rest on active inference, which in turn emphasise that an agent's actions influence its sensations. Indeed, active inference holds that since the observations that agents make depend on their actions, their generative models must build expectations about outcomes that would follow different sequences of actions. Within this active inference framework, in which actions are considered in terms of expected sensory consequences, curiosity has been associated with "active sampling of the environment to minimize uncertainty about hypotheses - or explanations - for states of the world" [76].

To explain their account of curiosity, authors have found it useful to outline how the resolution of different types of uncertainty is associated with different types of behaviour [76]. In contrast to perceptual inference, which they propose resolves uncertainty about the causes of sensory outcomes under a given sequence of actions (i.e., a given policy), curiosity-related behaviours, they argue, resolve uncertainty through the choice of certain policies. Specifically, curious agents will choose policies that, by exposing them to novel combinations of hidden states and outcomes, allow them to discover the way these outcomes are generated. In other words, according to the PP framework curiosity relates to agents pursuing those policies that, in affording novelty and epistemic learning, improve generative models in the long run. However, given that psychologists tend to think of curiosity as a state first and foremost (even though such states may indeed be associated with behaviours), it is important to consider how such claims translate to the level of the experience. Here, it is therefore useful to refer to characterisations of curiosity as the experience of *expected* uncertainty reduction that is made possible through one's actions [77].

Staying on such a phenomenological level, it is clear to see how curiosity (a state of expecting uncertainty to be reduced) will generally lead to increased or continued allocation of cognitive resources to a stimulus (or certain features of a stimulus) that affords epistemic learning. Narrowing down to the context of a music listening episode, curiosity would constitute feeling compelled to attend to the music, (or specific streams within the music), that seem to afford the opportunity to better understand what is being heard. Here, it is useful to exemplify how adopting a PP framework aids the development of a model of music engagement: indeed, while some earlier accounts have tended to emphasise the importance of novelty (or high information content) in inducing curiosity, the PP account is able to account for the fact that even low information content events (or familiar materials) can trigger curiosity [63]. That introduction of repetition into contemporary art music increases interest and enjoyability has previously been demonstrated [78]. In emphasising how agents are driven by learning, the PP framework makes clear why repetition or low information content in a particularly complex (high entropy) musical sequence can induce curiosity and interest: namely, thanks to the promise of learning that these events afford, in the context of a sequence that seemed unlearnable until then.

In any case, the proposal that we become curious about music at those moments that seem to afford an opportunity to learn coheres well with another simple proposition: that "curiosity allocates attention, in a way that does not itself consume attention" [75,79] or in other words that curiosity exists to help agents efficiently 'decide' where and when to attend. Further, such a proposal aligns well to increasingly popular accounts that emphasize a role of expected learning progress in driving curiosity [80,81].

3.3 Accounting for attention, meta-awareness and mental action

Although research questions, efforts and outputs on the topic continue to grow, attention constitutes one of the earliest psychological processes accounted for in terms of the PP framework. According to the PP framework, if perception is inference about causes of sensory input, then attention is inference about the uncertainty – or in other words precision – of those causes [70,82]. Precision-weighting means using estimates of data's reliability to determine how much influence said data should have on the inferential process. In the current literature, the notion of precision-weighting is widely used when accounting for attentional processes.

Specifically, attention has been formalised as precision of (or confidence in) beliefs about how observations are related to the states of the world that generated them [72,83,84]. Against this background, attentional control has been described as the deployment of precision [85,86], whereby to attend means to increase the extent to which an agent believes their observations accurately map onto actual states of the world. Technically speaking, attending to a certain stimulus (deploying precision) increases the relative weight on inferences made on the basis of those particular observations. Intuitively speaking, when we pay attention to auditory stimuli, we are enabling what we hear to more greatly influence our predictions, as well as permitting greater confidence in our interpretation of the heard sounds.

Recently, the PP framework has begun to accommodate the fact that organisms need to become aware of moments when they are no longer attending. The ability to explicitly observe the ongoing contents of a conscious episode is increasingly accounted for in terms of "opaqueness". A state is said to be opaque when its underlying processes can be attended to using introspective attention [87]. Based on this idea [73], attentional states have been described as second-order states that allow first-order perceptual states to become opaque. In turn, meta-awareness has been described as a third-order state that allows (second-order) attentional states to become opaque [88].

Specifically, in their formalisation of sustained selective attention, Sandved-Smith and colleagues [88] operationalised meta-awareness as the higher level in an agent's predictive model that modulates the precision (and accordingly opaqueness) of second-order attentional states; thus allowing agents to distinguish when they are attending to a continuous sensory stimulus, from when they are in fact distracted or mind-wandering. In turn, they accounted for the mental action of re-attending to a stimulus in terms of the active inference imperative for organisms to choose actions that bring them closer to their generative model's preferred / expected state. In brief, active inference stipulates that policies are more probable if they minimise free energy. In the context of a sustained attention task, the generative model's preferred / expected state, associated with minimal free energy, is the state of attending. In other words, while noticing one is attending would not cause any surprise, noticing one is mind-wandering would result in surprise that would need to be minimised.

Taken together then, PP framework offers a useful account of how cycles of attentional engagement, mind-wandering and mental action emerge. Once again, it is relevant to consider how such insights from the PP framework may benefit the development of a model of music engagement. Here, we argue that the PP framework allows various processes involved in engagement to be accounted for with the same terms. Indeed, music psychologists implicitly recognise that (as is the case for all sustained attention tasks), attentive music listening must sometimes give way to mind-wandering (e.g., [89]). With the PP literature able to formalise two different ways by which attention may be redeployed after such mind-wandering episodes (namely, thanks to stimulus-driven curiosity or thanks to the stimulus-independent brain processes that are meta-awareness and mental action), it offers an appealingly unified perspective from which to consider a sustained attention activity like music listening.

3.4 Accounting for positive valence

Valence can be broadly defined as the positive and negative character of emotion. Since – alongside curiosity and heightened attention – the majority of engaging music listening episodes entail positively valenced experiences [90], we end our review of relevant PP literature with a consideration of PP accounts of valence.

Interestingly, while early PP accounts tended to posit emotion states as active inference based on the causes of interoceptive signals [91], current work tends to explain emotion in terms of active inference based on perception of sensory stimuli. Specifically, valence is increasingly accounted for in terms of the rate of free energy or prediction errors over time [81,92–94]. Joffily & Coricelli [94] proposed that a positively valenced state is elicited in the transition from a state of high to low surprise, and as such their account is similar to those arguing that positive affect reflects a shift from a high free-energy and thus less valued state to a low free-energy and thus more valued state (e.g., [95]).

Most recently, Hesp and colleagues [96] have extended previous work on valence through the use of deep active inference. In their account, moments of experiencing positive valence occur when an agent is reducing error faster than expected (i.e., during error reduction acceleration) while experiences of negative valence occur when it is reducing error slower than expected (i.e., during error reduction deceleration). Interestingly, this proposition that valence is inferred from model fitness [96], is in line with findings that positive valence begets behaviours that show greater reliance on prior expectations [97,98].

Taken together, PP accounts resonate nicely with the idea that if curiosity is a sense of where progress in learning can be made, positive valence is what is experienced when the actual predictive progress is made [77]. In the following section we use such core notions to inform the main claims of our model.

4. A model of time-varying music engagement

Whether used as background stimulation [61] or as the sole intended focus of attention, engagement with music tends to wax and wane over time. Here, based on our consideration of empirical, theoretical and computational work, we propose a model of time-varying music engagement that we hope will increase the effectiveness and value of future research on the topic.

INSERT FIGURE 2 ABOUT HERE.

1. As an overarching claim, we propose that, over the course of an extended listening episode, music engagement may constitute several cycles of curiosity, attention and positive valence. Within this, we suggest:
    a. that the induction of moments of curiosity, the beginning of (music-driven) cycles, may align with the absolute beginning or new sections of the music (e.g., the chorus), with sources of change and novelty in the music (e.g., entrance of instruments, the voice) or with moments of repetition or low information content in highly uncertain contexts: all leading the listener to seek to understand how such elements in the music could have emerged and will evolve. In PP terms, a curious agent (listener) pursues policies (listens) such that, in affording novelty and epistemic learning (in allowing one's self to be exposed to new or unpredicted material), it improves its generative models (enables better predictions) in the long run.
    b. that heightened selective attention will always follow the induction of music-driven curiosity; this, in turn, allowing swifter updating of the listeners' generative model of the music. In other words, an agent (listener), having experienced curiosity in response to music, will attend (increase its confidence in how observations are related to states) so as to optimise the rate at which its model of the music improves.
    c. that positively valenced affect will tend to always come *after* the onset of attention, even if it also overlaps with it. This is thanks to an updated, more accurate, generative model allowing accelerated prediction error reduction.
2. In another key contribution, we emphasize that cycles of curiosity, attention and positive valence during music listening are interspersed with moments of mind-wandering. Further, we suggest that:
    a. moments of mind-wandering may be at least partially explained by redundancies in the music such as continuous repetition in low complexity music.

   b. while mind-wandering is antithetical to attentional engagement, it may sometimes overlap at least slightly with the experience of positive valence. Indeed, since positive valence is associated with (better-than-expected) accelerated prediction error reduction, any moments at which error reduction capacity reaches floor levels may be expected to overlap with moments of mind-wandering (or in other words disengagement).
3. Importantly, we suggest that two types of situations may lead to a refocusing on music after an episode of mind-wandering:
   a. situations where features in the music trigger curiosity (see 1a) and,
   b. situations where meta-awareness allows the listener to realize they are no longer attending. In PP terms, moments of mind-wandering become visible thanks to the third-order level in a deep generative model (i.e. meta-awareness) that allows the lower/second level (attention levels) to become opaque. Here, it is important to explicitly note that in such situations, where meta-awareness serves as a 'trigger' to attention, the cycle of engagement does not begin with a curiosity component, but rather with an abrupt increase in attention.
4. Last but not least, we argue that a number of extrinsic factors will modulate both overall levels of engagement and how it changes over time. We suggest that:
   a. in terms of complexity, music particularly low in complexity will lead to reduced engagement given there is little to trigger experiences of curiosity (and, consequently, attention). It will also determine the nature of 'music triggers' of engagement, whereby in highly complex, unpredictable music, lower rather than higher information content, may afford moments of heightened engagement [63,65,68,99].
   b. in terms of individual differences, expertise, for instance, will increase the extent to which curiosity is influenced by musical structure as well as increase overall levels of attentional engagement ([63] and current data); this thanks to expert listeners' more sophisticated generative models allowing them to better recognise opportunities for epistemic learning.
   c. the listening situation and context will influence the degree to which a listener will choose to actively listen (engage) as opposed to allow music to remain in the background; an idea previously captured by the notion of the aesthetic attitude [100,101].

5. Future directions and implication

Having presented a model of music engagement that is inspired by the PP framework, it seems important to revisit the question: "Why do we need PP to explain music engagement?" Here, we argue that the PP framework is one of the only frameworks to bring curiosity, attention and valence together in a convincing way. As such, it provides a particularly parsimonious way of accounting for music engagement: a phenomenon that implicates these processes. Furthermore, by clarifying the relationship between these key psychological phenomena that seem intrinsic to music engagement, PP allows the opening up of new testable hypotheses, which – we argue – was largely missing from the music engagement literature. To the related question, "How might PP practically help in the study of musical engagement?", we suggest that future studies seek to directly test the various claims and assumptions of our model. Indeed, inspired by what we have presented, music science researchers with a background in programming and mathematics could seek to build markov decision models, run simulations and fit their obtained models to new or existing data on how music engagement unfolds [102]. Alternatively, experimental researchers could use our model to design and implement new hypothesis-driven research that is much-needed to advance understanding of music engagement.

For instance, our model puts forward the claim that increases in attentional engagement with music will always be preceded by either experiences of curiosity or conscious recognition (meta-awareness) that one was mind-wandering. We suggest some version of a self-caught experience sampling methodology could be used to examine whether this is indeed the case. Another assumption of our model, that is heavily inspired by the PP framework, is that both low and high information content events can trigger curiosity depending on the predictability or entropy of the music at that moment. Accordingly, an interesting question that our model raises is whether such effects can be seen with an implicit approach like ISC. To date, measurement of shared music engagement, using ISC, has produced data that is in line with our PP-inspired model: Indeed, it follows from our model that there would be low ISC (engagement) during minimalist/simple/familiar pieces since (due to their low complexity features) people are likely mind-wandering rather than attending [20]. Similarly, it follows from our model, that given their more developed generative models, expert listeners tend to show sustained (as opposed to decreasing) levels of ISC to repetitions of unfamiliar music [43]. We highlighted earlier in this paper that the ISC approach is limited in only indicating 'shared engagement' across listeners. However, this fact does not preclude the usefulness of future studies probing the possibility that repetition drives peaks in ISC in the context of unfamiliar or complex music.

Staying with the idea of repetition, a related direction for future work would be extending the model to explicitly formalise how music engagement changes as a function of repeated listenings. It is widely recognised that, in addition to music being highly repetitive across cultures, listeners also tend to seek out repetition in the form of re-listening to favorite songs [103]. We propose that such re-listenings provide listeners the opportunity to explore the still yet-to-be-learned aspects of the music while also providing enjoyment thanks to the high processing fluency that accompanies strong veridical expectations. Researchers have long pondered over listeners' seemingly contradictory drive to experience both novelty and familiarity in music. The PP framework could help formalise what is likely simply a musical manifestation of a more general occurrence; a phenomenon referred to in the literature as the exploitation versus exploration dilemma [74,104].

With regard to methodologies, we suggest that, given the limitations of those we have reviewed (e.g., behavioural report and ISC), future studies on music engagement would benefit from adopting additional ways of measuring music engagement. One highly ecologically valid approach that could be taken is to combine virtual reality with eye-tracking technology (e.g., as in [105]) to explore how, for example, listeners shift their attention between virtual displays of a target music's source, on the one hand, and distracting visual stimuli, on the other. Similarly, given that mind-wandering has been described as the antithesis of both curiosity [106] and attention, the probe caught experience sampling methodology could be used to examine how rates of reported mind-wandering relate to dynamic changes in curiosity and attention as suggested by our model.

Probe caught experience sampling methodologies could also be used to test the assumption that positive valence occurs at a very specific time in relation to curiosity and attention. Here, we point out that while our model relates positive valence to accelerated prediction error reduction and suggests it is most likely preceded by curiosity (and attention) and followed by mind-wandering, another type of positive experience of music may be expected to occur much earlier in the cycle than positive valence. Chills are pleasurable, often high arousal, sensations that are more closely tied to reward than emotion. Chills have tended to be associated with prediction violations per se [107] (see also literature on syncopation where prediction violation is related to pleasure [108–110]) and chills may therefore be expected to occur around those moments in which curiosity is triggered. Such an account is consistent with the idea that feelings of curiosity can be experienced as pleasurable [111]. It also highlights the likelihood that chills and positive valence may differ in the extent to which they reach conscious awareness (where chills, in being driven by prediction violation, may be more conscious than positively valenced feelings). Here, we note that the current model as it stands does not specify the dynamics of feelings of reward over time. However, should future empirical work support the above speculations, it would be useful for a revised version of the model to be extended in this way.

Other less urgent but still pertinent directions for future work include formalising those periods of music engagement that occur on the level of meaning making or that involve other non-visual sensory domains in the form of, for example, visual imagery [21,112]. Here, we argue that insights from the PP framework (e.g., see [113]) may continue to prove beneficial. Further, since the concept of engagement has risen in use in the context of aesthetics and media, and since predictive mechanisms are held to be crucial in many of these domains (e.g., [114]), our model could be adapted for use in a host of other non-music contexts.

Finally, we stress that besides providing testable hypotheses as to how music engagement unfolds, a major implication of our work is its potential to promote our general understanding of key psychological processes. Indeed, while there has been a steady evolution in thinking about how curiosity arises [115], an exciting development is the growing work on how it leads to enhanced attentional engagement [79,116], and memory (e.g., [23]). Similarly, new work is interrogating the idea that the arts promote knowledge and understanding [117,118], and that art appreciation involves prediction, learning and insight [90,114,119]. We suggest our model provides a principled basis for exploring such ideas further.

Authors' Contributions

DO provided the original conception and design of the article, participated in analysis and interpretation of data, and drafted and revised the MS critically. IM substantially contributed to the article's content and design, led data acquisition, analysis and interpretation, and co-drafted and revised the article critically.

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Competing interests

The authors have no competing interests to declare.

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Figure Captions

Figure 1: Showing A) Overview of sample, task and experimental conditions. B) Amount of deployed attention as a function of expertise and musical style. List of pieces, data and code can be found in supplementary materials.

Figure 2: Model of time-varying music engagement. Music engagement constitutes several cycles of (curiosity), attention and positive valence, interspersed with moments of mind wandering (here, 5 cycles are shown). Refocusing on the music after an episode of mind-wandering is due to musical triggers or mental action, while modulatory factors include complexity, individual differences and listening context.