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Accounting for expressions of curiosity and enjoyment during music listening

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Author note

We have no known conflict of interest to disclose.

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Abstract

Music induces surprise and uncertainty in listeners as it unfolds. However, it remains unexamined whether it is also able to induce waxing and waning feelings of curiosity, how such feelings relate to the enjoyment of music, and what role music's information theoretic structure and listeners' expertise and trait curiosity may play. Here, we characterized melodies using a computational model and required participants to report on their experience of them as they unfolded. In a first experiment, listeners indicated, when cued, how curious they were as to how the melodies would continue. In a second, a further set of participants indicated, when cued, how much they were enjoying the melodies, before completing a multidimensional assessment of curiosity. We found a positive association between curiosity and note information content (IC, surprisingness) that was more pronounced in low entropy (highly predictable) contexts. However, we found that curiosity ratings of listeners with no music-theory training (and little/ no experience playing music) were less influenced by musical structure and more driven by judgments of stimulus valence. Finally, we showed that two subgroups of curious people, revealed using cluster analyses, did not differ in how well their curiosity ratings were explained by IC and entropy, but differed in the extent to which their unfolding enjoyment of music changed as a function of IC. Taken together, our results demonstrate that musical structure interacts with musical background to influence the emergence of felt curiosity during music listening, while trait curiosity further influences how listening enjoyment emerges.

Keywords: *music, curiosity, emotion, expertise, epistemic emotion, information seeking*

Introduction

Curiosity is a research topic of great importance as a state and trait that allows humans to make important decisions, both with regard to what knowledge to seek out and how long to engage with people, places and information in the environment. State curiosity, specifically, is seen as an intrinsically motivated information-seeking state that is characterized by a momentary desire for knowledge (Loewenstein, 1994). Suggested to be influenced by novelty, complexity and expectation violation, state curiosity not only drives exploratory behaviours that lead to learning across the life span but has also been associated with reward, learning, and control processes in the brain (Gottlieb, Oudeyer, Lopes & Baranes, 2013; Kidd & Hayden 2015; Gruber, Gelman, & Ranganath, 2014; Sakaki, Yagi, & Murayama, 2018; Murayama, FitzGibbon, & Sakaki, 2019; Cervera, Wang, & Hayden, 2020). In turn, the influence of trait curiosity, characterized as a tendency to experience state curiosity in everyday life, has been observed across various domains of perception and cognition. However, despite the ubiquity of contexts in which state and trait curiosity are clearly relevant in guiding engagement with the environment and influencing ensuing behaviour, the contexts in which they are explored remain fairly limited.

From epistemic and perceptual to information theoretic conceptualizations of state curiosity in the arts

The large majority of experimental paradigms that have explored state curiosity have focused on examining so-called epistemic and perceptual forms of state curiosity. Epistemic curiosity, the desire to obtain new knowledge such as concepts and facts, has often been examined by presenting trivia questions to participants, requiring them to report their interest in the answers to those questions, and monitoring their willingness to wait for said answers (e.g. Kang et al., 2009). In contrast, perceptual curiosity - the orientation towards, and interest and attention given to sensory stimuli - has largely been examined by acquiring and analysing measures of participant engagement with distorted or compromised visual stimuli (e.g. Jepma Verdonschot, Van Steenbergen, Rombouts, & Nieuwenhuis, 2012). More recently, a number of studies have employed so-called lottery paradigms to study factors influencing state curiosity as it unfolds. In such studies, uncertainty and expected reward, amongst other variables, are carefully manipulated whilst the desire participants show for advance knowledge of their actions outcomes is tracked (van Lieshout, Vandenbroucke, Müller, Cools, & de Lange, 2018; Charpentier, Bromberg-Martin, & Sharot, 2018; Kobayashi & Hsu, 2019).

However, while all such studies have been invaluable in exploring the factors driving, and the brain networks involved in, curiosity induction and release (Kang et al., 2009; Jepma et al., 2012; Kidd & Hayden, 2015), the need for new paradigms with which to study curiosity is ever more evident. As for most growing research areas in the field of psychology, the assumption is that use of a wider variety of methods and stimuli will lead to new insights and also help in resolving discrepancies in existing empirical findings. Amongst others, discrepancies in current research on curiosity include varied findings regarding the nature of the relationship between uncertainty and curiosity, whereby both linear and non-linear relationships have been found between the two variables (van Lieshout et al., 2018; Dubey & Griffiths, 2020).

Against this context, and given their ecological validity and ubiquity, arts and related media are arguably a still relatively untapped resource in the goal towards better understanding curiosity. Not only is it widely accepted that state curiosity is a primary ingredient of the experience of and engagement with artworks, but curiosity-related personality traits (such as openness to experience) have also been demonstrated to be important influences in this regard (Berlyne, 1954; Berlyne, 1966; Fayn, MacCann, Tiliopoulos, & Silvia, 2015; Silvia, Fayn, Nusbaum, & Beaty, 2015; Schoeller, 2015). The aesthetic domain thus presents both as a theoretically relevant stimulus domain with which to study state and trait curiosity, and as a uniquely valuable opportunity to explore the reward that can come from information seeking. Music listening situations, especially, may offer an optimal test bed for exploring state curiosity, thanks to decades of research couching music listening in information theoretic terms (Koelsch, Vuust & Friston, 2019).

Accounting for music-induced curiosity

Musical expectancy, explained by the brain's propensity to constantly make predictions (Dennet, 1991; Clarke, 2015), is considered one of the key mechanisms by which music can evoke emotion and meaning in music (Meyer, 1956). Critically, the development of psychological models to account for the musical predictions listeners make (e.g. Narmour, 1990; Schellenberg, 1997) has paved the way for computational tools with which the information theoretic properties of musical events can be quantified (e.g. Pearce, 2005; Pearce & Wiggins, 2012).

In the field of information theory, Information content (IC) is a quantity derived from the probability of a particular event occurring, and describes the lower bound on the number of bits required to encode an event in context (Mackay, 2003). In turn, entropy can be defined as the average level of information or uncertainty that is inherent in a variable's possible outcomes. Critically, in line with early studies using music theoretic approaches to characterize stimuli (Besson & Faita, 1995; Koelsch, 2012), musical events characterized as high in IC, have been shown to be experienced as surprising to listeners (Pearce, Ruiz, Kapasi, Wiggins, & Bhattacharya, 2010), while those high in entropy are associated with feelings of uncertainty (Hansen & Pearce, 2014; Hansen et al., 2016).

Furthermore, listeners display facilitated processing of low IC events in speeded listening judgments tasks (Bharucha & Stoekig, 1986;1987; Omigie, Pearce & Stewart, 2012), while electrophysiological data reveal both cortical and subcortical sensitivity of the brain to parametric modulations of musical events' IC (Kim, Kim & Chung, 2011; Carrus, Pearce, &

Bhattacharya, 2013; Omigie, Pearce, Williamson & Stewart, 2013; Pearce, Ruiz, Kapasi, Wiggins, and Bhattacharya, 2010; Omigie, Pearce, Lehongre, Hasboun, Navarro, Adam, and Samson, 2019; Cheung, Meyer, Friederici & Koelsch, 2019). Further demonstrating the importance of this aspect of expectancy in music processing, melodic expectations are observable in children (e.g. Politimou, Douglass-Kirk, Pearce, Stewart, & Franco, 2020) while pitch and timing expectancy have considerable implications for emotional responses and reward during music listening (Sauve, Sayed, Dean & Pearce, 2018; Egermann, Pearce, Wiggins, & McAdams, 2013; Gold, Pearce, Mas-Herrero, Dagher & Zatorre, 2019). However, insights into whether any music-induced curiosity experiences reported by listeners mirror music's information theoretic structure, remain, as yet, completely unexplored.

Indeed, according to theoretical and empirical work that emphasizes a role for expectation violation and uncertainty in inducing curiosity (Gottlieb et al., 2013; Kidd & Hayden, 2015), high IC and high entropy events in music should lead not only to surprise and uncertainty but should also influence a listener's desire to know how a piece of heard music will unfold. For instance, greater curiosity following high IC musical events could be seen as a natural consequence of the fact that feelings of surprise causes the listener to recognize a gap in their knowledge about the music's unfolding structure (Litman, 2005). Interestingly, while earlier work in music psychology studied the influence, on their own, of event IC and entropy, recent studies suggest that listeners' responses to music over time are often the result of an interaction between these two information theoretic measures (e.g. Quiroga-Martinez, Hansen, Højlund, Pearce, Brattico, & Vuust, 2019 a, b; Bianco, Ptsyzanki, & Omigie, 2020). According to contemporary accounts of predictive coding in the brain, expectancy violations (prediction errors) are "precision-weighted", meaning that they are experienced as greater in predictable (low entropy) compared to less predictable (high entropy) environments. In line with these accounts, findings from studies using musical stimuli confirm that the entropy of stimuli influences the magnitude of putative prediction error responses such as the MMN and the pupil dilation response (Quiroga-Martinez, et al a, b; Quiroga-Martinez, Hansen, Hoejlund, Pearce, Brattico, & Vuust, 2020; Lumaca, Trusbak Haumann, Brattico, Grube, & Vuust, 2019; Bianco et al., 2020). An interesting question therefore is whether feelings of curiosity are jointly influenced by IC and entropy, as opposed to these two measures acting alone to influence curiosity.

Another interesting question pertains to which, if any, other contextual factors influence curiosity during music listening. Recent accounts of curiosity emphasize that, beyond influences like surprise and uncertainty, curiosity is also modulated by the valence of the stimuli being experienced (Marvin & Shohamy, 2016; van Lieshout, Traast, de Lange, & Cools, 2019). In these studies, advance information about positive outcomes has been shown to be valued more highly than advance information about negative outcomes (Charpentier, Bromberg-Martin, & Sharot, 2018) and participants have been shown to prefer to learn about future desirable outcomes and remain ignorant about future undesirable ones (Charpentier, Bromberg-Martin, & Sharot, 2018). Such valence effects have been shown in the context of lottery tasks (van Lieshout et al., 2019) and during exposure to paradigms using trivia facts (Marvin & Shohamy, 2016), amongst others. However, it remains an open question whether valence judgments of the heard stimulus may also influence curiosity during music listening.

Indeed, since studies indicate that judgments about music can be made very rapidly after the music begins (Belfi, Kasdan, Rowland, Vessel, Starr, & Poeppel, 2018), one possibility is that lay listeners, who tend to focus on affective experiences when listening to music (Müller, Höfel, Brattico, & Jacobsen, 2010) may make judgments regarding how pleasant the stimulus is, which then guide the feelings of curiosity that they experience and report. In contrast, those with more explicit knowledge of how music is constructed and structured may show curiosity ratings that are less driven by valence judgments and more driven by music's information theoretic structure. Taken together, how self-reports of waxing and waning feelings of curiosity during music listening is associated with the information theoretic properties of heard events, a listener's valence judgments of the pieces these events are in, and the background of the given listener, present as interesting questions for which answers are possible.

From music-induced curiosity to accounting for musical enjoyment.

Finally, the widely hypothesized links between curiosity and reward (Murayama et al., 2019) arguably call for investigations not just into how curiosity is induced during music listening, but also into whether the state of being curious is experienced as rewarding or not. Interestingly, just as we propose that curiosity might be explained by an interaction between IC and entropy, so also does recent evidence suggest that IC and entropy interactions can explain reward from music (Cheung, Harrison, Meyer, Pearce, Haynes, & Koelsch, 2019). Following the use of a computational model to characterize IC and entropy of chords in pop song chord progressions, Cheung and colleagues required participants to continuously rate the pleasure felt in response to individual chords in the heard chord progressions. The authors showed that both chord IC and entropy jointly explained musical pleasure, whereby high IC was pleasurable at points of low entropy and low IC was pleasurable at points of high entropy (Cheung et al., 2019). A similar pattern, whereby listeners' positive judgments tended to favour low IC events in uncertain contexts, has since been shown using another set of ecologically valid musical stimuli (Gold et al., 2019).

However, while these studies show the power of information theoretical approaches in explaining music-induced reward, an important question that remains is whether individual differences in information seeking related traits - specifically, trait curiosity- may modulate this relationship. Broadly inspired by a significant body of work that debates whether curiosity is a positively or negatively-valenced experience (e.g. Litman, 2005), a recent psychometrical tool for measuring individual differences in curiosity emphasizes the multiple dimensions that trait curiosity can be considered to have (Kashdan, Stiksma, Disabato, McKnight, Bekier, Kaji, & Lazarus, 2018). According to the rationale behind Kashdan's five dimensional curiosity (5DC) scale, the extent to which an individual takes pleasure in novelty and uncertainty (Joyful exploration), feels discomfort when they recognise an information gap (Deprivation sensitivity), or accepts the stress of new and uncertain experiences (Stress tolerance), all combine with the interest that they have in others (Social curiosity) and in thrilling activities (Thrill-seeking), to provide a multi-faceted picture of the ways in which their curiosity is felt and expressed.

Kashdan's 5DC scale has been able to account for differences in media consumption in different groups of 'curious people' (identified using clustering techniques). Here, we argue that characterizing participants with the help of this scale may also help to account for variations in how music is dynamically enjoyed over time as a function of musical structure. Specifically, we propose that those listeners whose curiosity profiles are characterized by enjoyment of novelty and uncertainty and a tolerance of the stress that these can induce (i.e. those listeners that are high in joyful exploration and stress tolerance, and low in deprivation sensitivity), may, be expected to enjoy such points in music more than other types of listeners.

In sum, the current paper aims to better understand music engagement and reward by examining the role of information theoretic structure and listeners' musical background and state and trait curiosity in this regard. More broadly, it seeks to demonstrate the potential usefulness of employing music as a testbed for studying curiosity, both as a state and a trait. In Study 1, we tested the hypotheses that listeners, especially those possessing a sensitivity to music structure afforded through music theory training, would show greater curiosity as to how music will unfold following high IC relative to low IC notes, and this particularly in low entropy contexts. We also tested the hypothesis that curiosity ratings would show associations with listeners' valence judgments of heard musical stimuli, and this to a greater extent in listeners lacking training in music theory. In Study 2, we then turned our attention to the patterns of reward derived from the structure of unfolding music. There, we tested the hypothesis that individual differences in trait curiosity modulate the way in which enjoyment unfolds as a function of musical structure.

Study 1

The aims of Study 1 were three-fold. Firstly, it sought to examine whether the IC and entropy of notes influence, whether independently or jointly, how listeners' experience curiosity in response to unfolding music. Secondly, it asked whether, as demonstrated in other domains, curiosity is associated with valence judgments of the stimulus being experienced. Finally, in light of a significant body of work showing that expertise influences how music is engaged with, it examined whether training in music theory influences the strength of the relationship between self-reports of state curiosity and information theoretic structure during music listening.

To achieve these goals, a computational model of melodic expectation (Pearce, 2005) known as IDyOM (Information dynamics of music) was used to characterize the IC and entropy of notes in real melodies and a music theory-trained and non-music theory trained group of participants were required, when cued by a counting down clock hand, to report on how curious they were about how the given melody would unfold (Omigie et al., 2012). At the end of each melody, participants indicated how pleasant they had found the melody allowing us to compare how well IC and entropy on the one hand, and ratings of valence on the other were associated with curiosity ratings provided by the two groups.

We predicted that participants would generally report greater curiosity for how music would unfold following high IC (more surprising) relative to low IC notes. Further, in line with the idea that prediction error is influenced by the precision of one's predictive model (which is, in turn, influenced by the entropy/predictability of stimulus context), we hypothesised that any effect of IC on curiosity would be greater in low than high entropy contexts.

Here it is important to note that our modelling of the stimuli using IDyOM assumes a situation where all listeners possess the minimum level of exposure to the relevant musical environment (here to tonal music from the western cannon) that is necessary them to be able to make fairly accurate predictions about the unfolding musical structure. Here it is also worth mentioning that the musical knowledge that we believe this exposure affords to a listener is captured by IDyOM's long term model component (see the Methods section for details) which simulates long-term exposure to music by learning the regularities in a corpus of music that it is provided with (where the corpus of music could be from any culture (western or non-western) or style (e.g. folk or contemporary within western music)).

Accordingly, we propose that any differences in the way in which the groups of listeners report on their curiosity experience is a direct consequence of the levels of explicit knowledge of musical structure they possess and the ensuing approach they take when listening to music. Specifically, we suggest that those listeners who have formal training in music theory (and therefore in the methods and concepts composers use in creating music) may process musical information in a way that is shaped by the explicit knowledge that they (unlike non-trained music listeners) have about musical structure (Bigand & Poulin-Charonnat, 2016). Explicit knowledge of musical structure here could include, amongst others, the ability to recognize and label intervals, and to infer and label the harmonic structure implied by the heard melody. We suggest that this explicit knowledge may drive listeners with theory training to listen to in a more conscious and deliberate – or in other words, in a more analytic- way. In addition to anticipating that music-induced curiosity in participants with no training in music theory will show less sensitivity to information theoretic structure, we also hypothesized that their ratings would be guided to a greater extent by valence judgments of the melodic stimuli being heard (Marvin & Shohamy, 2016; van Lieshout et al., 2019).

Materials and Methods

Participants

The study was approved by the University Ethics Committee and participants gave written informed consent in accordance with the Declaration of Helsinki. The sample size of 40 was based on a previous study that investigated the effect of IC level on the unexpectedness ratings typical listeners assigned to cued notes (Omigie et al., 2012, Table 4). Our calculations using that study revealed an effect size of Cohen's $d = 0.84$ and power analysis (using the *pwr* package in R) recommended the testing of at least 13 participants (*alpha* = 0.05 and *beta* = 1 - 0.8). 40 participants were however tested i) to allow for the exploration of entropy (in addition to IC), ii) to allow potential differences between the two groups to be explored and, finally, iii) based on the assumption that listeners might find it more difficult to introspect on their feelings of wanting to hear more (i.e. curiosity) than on feelings of being surprised (experiencing something unexpected) and may thus provide noisier ratings data than in previous work.

To ensure timely recruitment of participants with formal music theory training, posters were placed in those parts of the home university campus that were most reliably frequented by music students and teaching staff. In the initial stages of data collection, all participants were invited to complete the study and only afterwards required to provide answers to questions (taken from a well-known questionnaire of musical sophistication: The Goldsmith Musical Sophistication Index: Müllensiefen, Gingras, Musil, & Stewart, 2014) that inquired after years of formal training in music theory, years of regularly practicing an instrument, and amount of time spent listening to music daily[1]. In the final stages of data collection, however, individuals interested in participating were pre-screened for musical background so that the remaining target number needed for each group could be attained.

The final sample of 20 individuals who reported no formal music theory training (No theory training group: *Male* = 6, *Female* = 14; all with 0 years of theory training) and 20 individuals who had undergone some formal musical training (Theory- trained group: *Male* = 4, *Female* = 16; range = 1 year to 10 or more years), also differed with respect to the number of years of daily practice of a musical instrument they reported. Specifically, while in the no theory training group, 65% had never regularly played an instrument and only 15% had experienced 6 or more years of doing so, 100% of participants in the training group had played an instrument for at least a year, and as much as 70% had played an instrument for 10 years or more. The two groups were however seen to be similar in amount of daily music listening ($t(38) = -1.00$, $p = 0.32$) and did not differ with respect to age (No theory training: $M = 27.15$, $SD = 6.23$, range = 21 to 39; Theory Trained: $M = 28.7$, $SD = 5.89$, range = 24 to 46; $t(38) = -0.81$, $p = 0.42$). All participants were paid for their participation in the study.

Materials and Stimuli

Melodies of 32 hymns from a Church of England hymnal (Nicholson et al., 1950) were played in their original keys and rendered as MIDI files using the grand-piano acoustic instrument of a Roland sound canvas (SC-88) MIDI synthesizer. The melodies varied in length from 32 to 64 notes. To ensure participants had sufficient time to report on their

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[1] The questions were: How long have you had formal training in music theory? (possible responses: 0 / 0.5 / 1 / 2 / 3 / 4-6 / 7 or more years); How long have you engaged in regular, daily practice of a musical instrument (including voice) ?(possible responses: 0 / 1 / 2 / 3 / 4-5 / 6-9 / 10 or more years); How long a day do you listen attentively to music? (possible responses: 0-15 min / 15-30 min / 30-60 min / 60-90 min / 2 hrs / 2-3 hrs / 4 hrs or more per day).

subjective experience and reorient to the ongoing melody during rating tasks (see below), all notes had an inter-onset interval of 700 ms. The melodies were the same as those used in a previous study examining the ability of typical and amusic listeners to experience violation of melodic expectations on an implicit and explicit level (Omigie et al., 2012).

The IC and entropy of individual notes in the melody set were defined using IDyOM, a computational model of melodic expectation (Pearce, 2005), which, through unsupervised learning, generates estimates of IC and entropy of individual notes in a melody. The model configuration used here was comprised of both a long-term and a short-term model. The long term model, which simulates long-term exposure to music, was trained on 185 Chorale melodies, 152 Canadian folk songs and 556 German folk songs (903 compositions making up 60867 notes). In turn, the short-term model, which simulates a listener's experience during online listening, was trained incrementally over each stimulus melody as it unfolded. Pitch predictions were derived from a representation of the given note's scale degree and the size and direction of the interval preceding it, in line with previous recommendations (Pearce & Müllensiefen, 2017). IDyOM was run on the stimulus melodies after the rhythmic structure was removed. i.e. on the exact version of the MIDI files that participants were presented with during the experiment.

Figure 1 about here

Figure 1A shows the musical notation of a sample melody used in the study with the IC profile of the melody above it for illustration. All participants were presented with the same probe notes, which had been manually selected from each melody to follow certain constraints: namely, i) that probe notes appeared at least 6 notes after the melody commenced (this, to ensure a sufficiently clear context before participants were required to provide their ratings), ii) that the number of probe notes in each melody was roughly dependent on the length of the melody (a minimum of 2 probe notes in 32 note melodies and up to 6 probes in 64 note melodies; more being present in longer melodies so as maximise the number of probes), and iii) that the number of notes between probe notes nevertheless had a wide range (at least 7 notes between probe notes so participants had enough time to re-orient to the melody, but up to 26 notes between probe notes, to avoid participants being able to anticipate the occurrence of probe notes with any accuracy).

Procedure

The experiment was controlled by a computer program written in Java on a Dell desktop computer running Windows 10. Audio stimuli were presented to participants over Sennheiser HD-580 headphones. Participants were instructed to listen carefully to the presented melodies while attending to a visual analogue clock on the computer screen that would cue them as to when to report on their experience. The hand of the clock was at 12 at the beginning of the melody and remained there until it began to count down to the probe note in time with the melody. The hand of the clock pointed, in turn, to the 3, 6 and 9 o'clock positions before finally returning to the 12 o'clock position (See Figure 1B). At this point – after hearing the note that coincided with the clock hand returning to the 12 o'clock position- participants were required to indicate how curious they were about how the music would unfold. They were not specifically instructed to try to respond prior to the next note (i.e. the note after the probe note) as we assumed this would have led to rushed and potentially inaccurate reporting of their subjective experience.

Participants' curiosity ratings were provided on a Likert rating scale from 1 (Not at all curious) to 7 (Very curious). Participants indicated their responses by clicking on the appropriate buttons of the rating scale, which were presented below the clock (See Figure 1). In addition, participants were required to indicate, at the end of each melody, how pleasant they had found the melody (Likert rating from 1 (Not at all pleasant) to 7 (Very pleasant)) and whether it was familiar to them (Binary response: Yes, No). Familiarity information was collected to check for any differences across groups in familiarity with the melodic stimuli. Two practice trials were provided in order to familiarize participants with the task. The order of melodies was randomized for each participant and the experiment took approximately half an hour to complete.

Analysis

Analysis was conducted in R (R Core Team, 2014) using *lme4* (Bates *et al*., 2015) and *ggplot2* (Wickham, 2009) packages amongst others. To estimate the effect of note IC on music-induced curiosity for theory and non-theory-trained groups, a first linear mixed model was estimated with curiosity rating as dependent variable, note IC and music theory training (No theory training/ Theory trained) as fixed effects, and melody ID and participant ID as random effects.

Next, to examine the evidence for note IC and note entropy interactions in determining music-induced curiosity, and to explore how this may be different in the two participant groups, a second linear mixed model with curiosity rating as dependent variable, note IC, note entropy and music theory training as fixed effects (in addition to with melody ID and participant ID as random effects) was estimated.

Finally, to examine whether there was any evidence for a valence influence on music-induced curiosity in theory and non-theory trained groups, a model with curiosity rating as dependent variable, melody pleasantness rating and music theory training (No theory training/ Theory trained) as fixed effects, and melody ID and participant ID as random effects was estimated. For all analyses, simpler models were used to interrogate any significant interactions as relevant.

Results

A t-test revealed that there was no difference in the rate at which the two groups found melodies to be familiar (Theory training: *M* = 91.97% , *SD* = 0.12, No theory training: *M* = 91.10%, *SD* = 0.12, *t* = 0.23, *p* = 0.82). Accordingly, this variable was not considered further.

Comparing the effect of note IC on music-induced curiosity for theory trained and non-theory-trained groups.

First, we compared a linear model with curiosity rating as dependent variable, note IC and music theory training (No theory training/ Theory trained) as fixed effects, and melody ID and participant ID as random effects with one that did not include music theory training as a fixed effect. We found the more complex model to be superior (*ChiSq* = 73.82, p < 0.001).

This more complex model, when estimated, showed a main effect of IC (*B* = 0.03, *SE* = 0.01, *df* = 2086.6, *t* = 2.44, *p* = 0.01) and a significant interaction of IC and music theory training group (*B* = 0.16, *SE* = 0.02, *df* = 3367.79, *t* = 8.62, *p* < 0.001). Nevertheless, further linear mixed models examining the No theory training and Theory trained groups separately showed an effect of IC in both groups (With theory training: *B* = 0.19, *SE* = 0.01, *df* = 738.33, *t* =13.40, *p* < 0.001, 95% CI [0.16, 0.21; Without theory training: *B* = 0.04, *SE* = 0.01, *df* =1076.33, *t* = 2.81, *p* = 0.005, 95% CI [0.01, 0.07]).

Examining evidence for note IC and note entropy interactions on music-induced curiosity in both theory trained and non-theory trained groups.

To examine the evidence for note IC and note entropy interactions influencing music-induced curiosity, and to determine whether this potential influence differed between the two groups, a linear mixed model with curiosity rating as dependent variable, note IC, note entropy and music theory training (No theory training/ Theory trained) as fixed effects, and melody ID and participant ID as random effects was compared to two simpler models.

Critically, the more complex model was observed to be superior to both the simpler model that is reported above (i.e. the same but without entropy as a fixed effect: *ChiSq* = 11.73; *p* = 0.02) and to the simpler model without theory training group as fixed effect (i.e. with only note IC and note entropy as fixed effects; *ChiSq* = 84.4, *df* = 4, $p < 0.0001$)

Results of this more complex linear mixed model with all three fixed effects (i.e. note IC, note entropy, and theory training group) can be seen in Table 1. A significant three-way interaction between IC, entropy and music theory training group (*B* = 0.10, *SE* = 0.04, *df* = 3363, *t* = 2.67, *p* = 0.008, 95% CI [0.03, 0.18]) and a significant two-way interaction between note entropy and music theory training group (*B* =-0.52, *SE* = 0.16, *t* = -3.25, *df* = 3312, *p* = 0.001, 95% CI [-0.84, -0.21] was observed.

To examine how the two training groups differed with respect to a joint influence of entropy and IC, further simpler linear mixed models with curiosity rating as dependent variable, IC and entropy as fixed effects, and melody ID and participant ID as random effects, were carried out for the theory-trained and no-theory groups separately (see Table 2). While no significant effects were observed for the no-theory participants (all $p > 0.05$), analysis for the theory-trained group revealed a main effect of entropy (*B* = -0.25, *SE* = 0.12, *t* = -2.01, *p* = 0.05, 95% CI [0.49, -0.01] whereby greater curiosity was generally reported at lower entropy levels. It also revealed a significant interaction between IC and entropy (*B* = 0.06, *SE* = 0.03, *df* =545.43 , *t* = 2.03, *p* = 0.04, 95% CI [0, 0.12], suggesting that, as hypothesized, curiosity induction as a function of IC is dependent on entropy levels.

Figure 2 is a heat map showing how, for the theory-trained group, curiosity ratings changed as a function of IC at different entropy levels. There, it can be seen that while at lower to medium levels of entropy, theory trained participants found high IC notes more curiosity-inducing, the relationship between IC and curiosity ratings was more complex at higher levels of entropy (with many low IC events inducing greater curiosity than higher IC events).

Tables 1 and 2 about here

Figure 2 about here

Examining evidence for valence influence on music-induced curiosity.

Finally, a linear mixed model with melody pleasantness ratings and theory training group as fixed effects, and participant ID and melody ID as random effects was compared with a model that did not include theory training group as a fixed effect. The model with theory training group as a fixed effect was shown to be better than one without (*ChiSq* = 13.23, $df = 2$, $p = 0.001$).

Critically, in addition to revealing a main effect of pleasantness judgments on curiosity ratings ($B = 0.52$, $SE = 0.03$, $t(3311.3) = 15.92$, $p < 0.001$; 95% CI [0.46, 0.58]), whereby curiosity ratings were higher for notes in melodies later rated as more pleasant than for notes in melodies later rated as less pleasant, this model also revealed an interaction between theory training group and melody pleasantness ($B = -0.16$, SE = 0.045, $t(3312.2) = -3.6$, $p < 0.001$, 95% CIs= [-0.25, -0.07]). The interaction effect suggested that the strength of the influence of pleasantness rating was different in the two groups. However, follow- up analyses revealed that, for both participant groups, curiosity ratings were higher for notes in melodies described as pleasant than for notes in melodies described as less pleasant (no formal theory training ($B = 0.51$, $SE = 0.03$, $t(1581) = 16.50$, $p < 0.001$; formal theory training ($B = 0.36$, $SE = 0.03$, $t(1696) = 10.58$, $p < 0.001$))

Discussion

The main aims of our first study were to test whether listeners' subjective reports of experienced curiosity are associated with the information theoretic structure and valence judgments of the heard music, and whether the strength of either of these influences are in turn modulated by musical background (specifically, formal music theory training). Our results are valuable in showing all of these to be the case.

Firstly, in line with basic tenets of how curiosity is likely to be triggered (e.g. Gottlieb et al., 2013), we observed that all participants reported greater curiosity following high IC notes than following low IC ones. Further, in line with contemporary accounts of precision weighting in predictive coding (Friston, Mattout & Kilner, 2011; Palmer et al, 2019), and although this was the case only for those with theory training, we showed the expected pattern whereby the positive effect of IC on curiosity was greatest when entropy was low. Finally, we observed that the curiosity ratings given by those with no theory training were particularly well explained by the pleasantness ratings they later gave the melody.

Our findings suggest that while most listeners' curiosity patterns during music listening are at least somewhat influenced by the information theoretic structure of the heard music, those with some formal music theory training show an even greater influence of musical structure. Specifically, while those with no theory training only showed an influence of IC on their ratings, the curiosity ratings of those with training showed an influence of note IC that was modulated by note entropy. In contrast, the fact that the curiosity ratings of non-theory trained participants tended to be particularly well explained by the melody pleasantness ratings they later gave speaks to the potentially more global and affect-based way in such listeners may tend to engage with musical stimuli (Müller, Höfel, Brattico, & Jacobsen, 2010). Indeed, a listener with no theory training may be less likely to be - in the words of Eduard Hanslick (1986) - "continuously following and anticipating the composer's designs, here to be confirmed in his expectations, there to be agreeably led astray".

Grouping of participants in the current study was based on the presence or absence of music theory training. This was based on the assumption that, more than others, this specific form of training - which imparts explicit knowledge of the materials from which music is built and how such materials tend to be combined (Fallows, 2011)- may confer the analytic approach to music listening that has the potential to influence curiosity ratings. Specifically, we expected that an analytic approach to music listening would lead to a stronger reliance of the curiosity experience on information theoretic structure. However, we acknowledge that as the possession of theory training in our sample largely co-occured with the degree of regular practice of a musical instrument (and likely other aspects of music background that we did not measure), any differences we describe here (between the theory trained and non-theory trained groups), cannot be attributed to theory training alone.

Similarly, with regard to the relationship between curiosity during music listening and valence judgments of the heard melodies (provided at the end of the melodies), it remains unclear whether an initial judgment of valence could in fact have influenced curiosity ratings (given as the music unfolded), or whether the curiosity ratings provided during the task simply influenced the pleasantness ratings given at the end of the melody. Stimulus valence has been shown to influence curiosity in a number of other domains (e.g. Marvin & Shohamy, 2016), and the fact that judgments about music can be made very early (Belfi, Kasdan, Rowland, Vessel, Starr, & Poeppel, 2018) suggests this may be at play here too. In the current study, we do not seek to compare the degree of influence of musical structure and valence judgments within either group so much as we seek to compare how the strength of these influences differ *across* groups. However, future studies exploring music valence effects on unfolding curiosity ratings would benefit from having participants provide these self-report variables separately.

Taken together, Study 1 threw light on different factors (music-structural, stimulus valence, and musical background) that may influence the experience of curiosity during music listening. However, given that some accounts of information seeking emphasize the reward associated with information seeking (Murayama et al., 2019) while others pull into focus the negative-valenced feelings that may accompany feelings of a knowledge gap (Litman, 2005), an interesting question that remains is whether music events that tend to induce curiosity in listeners are experienced as enjoyable or not. Previous findings have shown that reward from music can be accounted for, at least partially, by information theoretic properties (e.g. Cheung et al, 2019). However, those studies did not take into consideration the role that individual differences in information seeking traits may be expected to play. In Study 2, we therefore asked whether individual differences in trait curiosity, in addition to any information theoretic structural features of the music, may account for how reward from music unfolds over time.

Study 2

The extent to which information theory can inform understanding of aesthetic emotions, judgments and appreciation has long been explored (Moles, 1966; Huron, 2008; Vuust & Witek, 2014; Meyer, 1957). As far back as 1712, Joseph Addison stressed the importance of surprise and curiosity in the experience of reward when he claimed, "*Everything that is new or uncommon raises a Pleasure in the Imagination, because it fills the Soul with an agreeable Surprize,[and] gratifies its Curiosity"*. Decades after Meyer's seminal text (1956) would propose that both the violation and fulfilment of expectations may be experienced as pleasurable, it is now evident that this seeming paradox may be due to the affordances of different musical contexts (e.g. Cheung et al., 2019). Building on this previous work, Study 2 addresses the possibility that people may nevertheless show different patterns of enjoyment of musical structure as a function of their trait curiosity profile (Kashdan et al., 2018). Specifically, Study 2 sought to examine whether individual differences in curiosity profiles can explain variations in whether violations of musical expectancy are experienced as enjoyable or not.

In brief, the current study sought to test the hypothesis that the enjoyment of music is a function of the interaction between information theoretic structure of heard music and an individual's curiosity profile. To this end we used the same melodic stimuli as in Study 1 but required participants to carry out two rating tasks with these melodies before filling out a multi-dimensional test of trait curiosity.

Specifically, in one of the rating tasks (identical to that used in Study 1) participants reported on their curiosity about how a given melody would unfold, immediately following the occurrence of probed notes (Omigie et al., 2012). In the second rating task (new to this study), they rated how much they were enjoying the melody they were hearing, where enjoyment was chosen as a measure of reward. Finally, participants completed the so-called Five-Dimensional Curiosity Scale (5DC; Kashdan et al., 2018): a multi-dimensional test of trait curiosity. One key benefit of this scale is arguably its ability to separate a tendency to experience curiosity as rewarding or pleasurable, from a tendency to experience it as a cause of frustration (Litman 2005). The 5DC's Joyous Exploration dimension seeks to capture positive emotions that come from new experiences and information, while the Deprivation Sensitivity dimension seeks to capture any distress induced by a perceived gap in knowledge (Litman & Jimerson, 2004; Loewenstein, 2004). The Stress Tolerance dimension captures the ability to deal with the stress and tension that comes from novelty and uncertainty while those high in the Thrill Seeking dimension may be expected to actively seek out intense experiences. Finally, the 5DC further includes a Social Curiosity dimension, which captures the desire an individual may crave for information about others.

Previous work had compared the four curiosity groups that emerged from cluster analyses using these five 5DC dimensions (Kashdan et al, 2018) in terms of group members' attitudes and behaviours. In the current study, all five dimensions of the 5DC scale (Joyous Exploration, Deprivation Sensitivity, Stress Tolerance, Social Curiosity, and Thrill Seeking) were once more used to identify emergent sub-groups, but here we aimed for two (instead of 4) groups that showed the greatest distinction from each other. Critically, in addition to anticipating that Stress tolerance and Deprivation sensitivity[2] alongside Joyous Exploration,

[2] These previously distinguished a group high in tolerance and appreciation of novelty and uncertainty (the so-called "Fascinated") from all other curiosity sub groups (Kashdan et al., 2018).

may be the most discriminating dimensions of the 5DC when two groups are aimed for, we also expected these two opposing groups to display opposing patterns of enjoyment of unfolding music structure.

Specifically, we predicted that while both sub-groups of curious people would report similarly high levels of curiosity in response to high IC relative to low IC notes, (with entropy once more showing a modulatory effect), they would nevertheless differ in terms of the patterns of music enjoyment they showed.

Methods

Participants

The study protocol was approved by the University Ethics Committee. All participants provided consent before commencement of the study. A total of 32 participated in the study following sample size considerations based on Study 1. However, as one participant was excluded based on likely not understanding the instructions (they showed evidence of poor English language skills at the end of the experiment and limited ability to clearly describe what they had done) and as 2 were excluded based on not completing both parts, a final total of 29 individuals (*Female* = 21) with ages ranging from 19 to 46 (*M* = 25.19, *SD* = 6.12) were included in the analysis. These participants possessed a range of musical backgrounds: approximately 33% had never undergone formal music theory or ever practiced an instrument, while 20% had both a minimum of 5 years of training in music theory and 5 years of daily practice of an instrument. The sample was primarily from Britain (40%) but included and represented 12 different nationalities overall. The majority of participants were enrolled at university (75%), with or without part-time employment and were paid for their participation. None of the participants in Study 2 had participated in Study 1.

Materials

The Five-Dimensional Curiosity Scale (Kashdan et al., 2018) which consists of 25 personality questions (five questions for each of the five curiosity dimensions namely Joyous Exploration, Deprivation Sensitivity, Stress Tolerance, Social Curiosity, and Thrill Seeking) was used to assess listeners' trait curiosity profiles. Agreement with statement were rated by participants on a 1-7 Likert scale (1= Does not describe me at all and 7 = Completely describes me).

All participants took part in two versions of the music listening paradigm. The first version, the curiosity rating task, was the same as Study 1, whereby participants were asked, when cued, to report on how curious they were about how the music would unfold (1 = Not at all curious, 7 = Very curious). In the new task, the enjoyment rating task, participants were instead asked to report, when cued by the clock hand, on how enjoyable they were finding the music heard (1= Not at all enjoyable, 7 = Very enjoyable). In both tasks, participants were also required to indicate, at the end of each melody, how pleasant they had found the melody (1= Not at all pleasant, 7 = Very Pleasant) and whether it was familiar to them or not (Yes, No). The melodic stimuli used were the same as those used in Study 1, but were split so that half were presented in the curiosity rating task and half were presented in the enjoyment rating task.

Procedure

Participants were presented with information on the purpose of the study, and then provided consent to participate. The order in which the tasks were carried out was counterbalanced. Following completion of the listening study, participants completed the 5DC questionnaire, and provided other background information in a survey implemented in Qualtrics (Provo, UT, USA).

Analysis

All analyses were carried out using R in the R studio environment (Rstudio Team, 2020). First, K-means clustering analysis (using the *stats* package) was used to obtain two opposing clusters of curious people. K-Means cluster analysis is an iterative algorithm that partitions a given dataset into *K* pre-defined clusters, where clusters are distinct and non-overlapping subgroups. Data points are assigned uniquely to clusters such that the sum of the squared distance between the data points and the cluster's centroid (arithmetic mean of all the data points that belong to that cluster) is at the minimum. In other words, data points in a cluster are kept as close as possible, while clusters are kept as far apart as possible. To ensure that participants were not clustered based on how curious they were over all, but rather on how their curiosity profiles differed (e.g. relative tendency towards high Stress tolerance rather than high Deprivation sensitivity or Social curiosity), K-means clustering of participants was based on the z-scores of participants' ratings. Specifically, each participant's responses to the 25 items were first z-scored, and then K-means clustering was based on participants' mean z-score across 5 items for each of the 5 dimensions.

Next, once two distinct clusters of individuals had been identified using K-means clustering, a mixed ANOVA with mean curiosity rating as dependent variable, curiosity dimension as within-subject independent variable and cluster group as between-subject independent variable, was carried out. To allow the characterization of the two clusters in terms of curiosity dimensions that discriminated them, follow-up non-paired t-tests (Bonferroni-corrected such that $p < 0.01$) were then used to evaluate how the two cluster groups compared with each other.

Finally, following naming of the cluster groups based on the curiosity dimensions that were found to discriminate them, we examined how the groups differed with respect to how their curiosity and enjoyment ratings were influenced. Specifically, a first linear mixed model with curiosity rating as dependent variable (with note IC and curiosity group as fixed effects and with melody ID and participant ID as random effects) was carried out with ratings from the curiosity rating task, before a second linear mixed model with enjoyment rating as dependent variable (and the same fixed and random effects) was carried out with ratings from the enjoyment rating task.

For both the curiosity and enjoyment dependent variables, further linear mixed models with entropy added as an additional fixed effect were estimated in an attempt to replicate findings from i) Study 1 showing an influence of IC-entropy interactions on curiosity, and ii) previous work showing that IC-entropy interactions can predict pleasure derived from music (Cheung et al., 2019). For all analyses, significant interactions were further investigated using simpler linear mixed models.

Results

Obtaining and characterizing the clusters

Descriptive statistics and the results of Pearson correlational analysis for the 5 curiosity dimensions can be seen in Table 3. Results showed that, overall, participants tended to report high levels of Joyful exploration and Deprivation sensitivity ($M = 0.49$, $SD = 0.36$; $M = 0.11$, $SD = 0.54$) and lowest levels of Stress tolerance ($M = -0.48$, $SD = 0.63$). Correlational analyses within these dimensions showed the strongest negative relationships between Stress tolerance and Deprivation sensitivity ($r = -0.49$, $p < 0.01$), suggesting those with high Stress tolerance tended to be low in Deprivation sensitivity. The next strongest correlations were between Social curiosity on the one hand and both Stress tolerance and Thrill seeking on the other (both $r = -0.37$, $p < 0.01$), whereby those showing high levels of Social curiosity were low in Stress tolerance and Thrill seeking.

Table 3 about here

Figure 3 shows the result of the K-means cluster analysis (carried out with an *nstart* of 20, and specifying the desired number of clusters as 2), and the mean z-scored curiosity values for each dimension for each cluster. A mixed ANOVA with cluster group as between-subject factor and curiosity dimension as a within-subject factor showed both the main effect of curiosity dimension and the interaction between curiosity dimension and cluster group to be significant (curiosity dimension: $F(4,108) = 12.82$, $p < 0.001$, $\eta 2G = 0.322$; cluster group: $F(1, 27) < 0.001$, $p > 0.05$, $\eta 2G=0$; curiosity dimension x cluster group: $F(4,108) = 11.13$, $p < 0.001$, $\eta 2G= 0.292$).

We carried out between-subjects t-tests to compare the two clusters for each dimension (Table 4). Levene's Homogeneity of variance tests revealed that only the Stress Tolerance dimension had unequal variance across the two groups. Accordingly for that dimension, a test assuming unequal variance assumed was also employed. Taken together, analysis revealed the two groups to differ with respect to Stress tolerance (unequal variance assumed: $t\ (20.5) = -9$, $p < .001$; equal variance assumed: $t(27)= -9.27$, $p < .001$), whereby this was lower in cluster 1 ($N = 15$, $M = -1$, $SD = 0.22$) than in cluster 2 ($N = 14$, $M = 0.08$, $SD = 0.39$). Cluster 1 was therefore named the *stress intolerant* cluster, while cluster 2 was named the *stress tolerant* cluster. The stress intolerant cluster (cluster 1) also showed a tendency towards higher Deprivation sensitivity ($t(27) = 2.13$, $p = 0.04$) and higher Social curiosity (equal variance assumed: $t(27) = 2.57$, $p = 0.016$) in line with observed correlational analyses, although, unlike the Stress tolerance dimension, these two dimensions did not survive Bonferroni correction for multiple comparisons.

Critically, comparison of the two curiosity groups showed they did not differ in the degree of formal training in music theory (stress intolerant group: $M_{likert} = 3.5$; $SD_{likert} =2.1$; range = 1 (0 years) to 7 (7 or more); stress tolerant group: $M_{likert} =2.29$; $SD_{likert} = 2.23$; range = 1 (0 years) to 7 (7 or more) ; $t(27) = 1.47$, $p = 0.15$) or the length of time spent playing a music instrument (stress intolerant group: $M_{likert} = 4.07$; $SD_{likert} = 2.43$; range = 1 (0 years) to 7 (10 or more years); stress tolerant group: $M_{likert} = 3.57$, $SD_{likert} = 2.77$; range = 1 (0 years) to 7 (10 or more years); $t(27) = 0.51$, $p = 0.61$).

Figure 3 and Table 4 about here

Trait curiosity influences on patterns of curiosity induction and enjoyment

Having identified and characterized the two obtained clusters, the final analysis steps aimed to determine the extent to which they differed with respect to the unfolding of felt curiosity and enjoyment during music listening. A between subject t-test revealed that there was no difference in the rate at which the groups found melodies to be familiar (stress intolerant: M = 95.55% , SD = 0.07, *stress tolerant*: M= 92.18%, SD = 0.12, t (27) = 0.92, p = 0.37). Thus familiarity was not considered any further in any of the analyses..

With regard to curiosity ratings, we first compared a linear mixed model with curiosity ratings as dependent variable, curiosity group and note IC as fixed effects, and participant ID and melody ID as random effects to one that did not include curiosity group as a fixed effect. The former was shown to be better than the latter (*ChiSq* = 13.02, df = 6, p = 0.04). The model with curiosity group included showed a significant effect of note IC (B =0.19, SE = 0.02, df = 881.51, t = 8.63, p < 0.001, 95% CI [0.15, 0.23]), whereby curiosity ratings were greater for high than for low IC notes in both groups (both p < 0.001), but no main effect of curiosity group or interaction of note IC with curiosity group (See Figure 4 and Table 5). [3]

With regard to enjoyment rating, a linear mixed model with enjoyment as dependent variable, curiosity group and note IC as fixed effects, and participant ID and melody ID as random effects, was seen to be better than one without curiosity group as one of the fixed

[3] Here it is worth noting that the superiority of the model that had curiosity group as one of the fixed effects (compared to the model without curiosity group) was likely due to a trend-level main effect of curiosity group on curiosity ratings.

effects (*ChiSq* = 15.94, *df* = 2, $p < 0.001$). Critically, in contrast to the model with curiosity as dependent variable (See Figure 4 and Table 5), the model with enjoyment as dependent variable revealed both a main effect of IC (*B* =-0.08, *SE* = 0.02, *df* = 912.92, *t* = -3.91, $p < .001$, 95% CI [-0.11, -0.04]) and a significant interaction between IC and curiosity group (*B* =0.11, *SE* = 0.03, *df* = 1178.89, *t* = 4, $p < .001$, 95% CI [0.06, 0.16]). Examination of the groups separately (Figure 4) showed that while lower IC levels were associated with higher enjoyment in the stress intolerant group (*B* =-0.07, *SE* = 0.02, *df* = 503.7, *t* = -3.82, $p < 0.001$), there was a trend towards the opposite effect in the stress tolerant group (*B* = 0.04, *SE* = 0.02, *df* = 381.37, *t* = 1.78, $p = 0.075$).

Influence of Trait curiosity and note IC and entropy interactions on music-induced curiosity and enjoyment.

Final analyses explored whether note IC- entropy interaction effects could be seen to be influencing curiosity and enjoyment ratings differently for the two curiosity groups. A linear mixed model with enjoyment ratings as dependent variable, curiosity group, note IC and note entropy as fixed effects, and participant ID and melody ID as random effects was compared to and observed to be no better than a model without entropy as a fixed effect (*ChiSq* = 0.90, *df* = 4, $p = 0.93$).

However, a similar linear mixed model with curiosity ratings as dependent variable, curiosity group, note IC and note entropy as fixed effects, and participant ID and melody ID as random effects showed superiority to one without entropy at trend level (*ChiSq* = 8.48, *df* = 4 , $p = 0.08$): its estimation replicated findings from Study 1 in revealing both a main effect of entropy (*B* = -0.41, *SE* = 0.20, *df* = 840.01, *t* = -2.10, $p = 0.04$, 95% CI[-0.80, -0.03]) and an interaction between IC and entropy (*B* =0.13, *SE* = 0.05, *df* = 892.82, *t* = 2.77, $p = 0.01$, 95% CI[0.04 0.21]).

Figures 4 about here

Table 5 about here

Discussion

Having demonstrated in Study 1 that information theoretic properties of music can predict the experience of curiosity during music listening, we used Study 2 to ask whether the most discriminating aspects of individual differences in trait curiosity influence how heard music is enjoyed over time. Participants completed an enjoyment rating task and the same curiosity rating task employed in Study 1, before completing a multidimensional assessment of curiosity. Using K-means cluster analysis on these dimensions of trait curiosity, we split the participants into two groups (distinguishable by the level of stress tolerance they possessed) and compared their performance in the different tasks.

With data collected using the enjoyment rating task, we showed that the group characterized by high intolerance to stress (as well as a tendency towards greater deprivation sensitivity and social curiosity) reported greater enjoyment of heard music immediately following low IC compared with high IC notes, while the group with high tolerance to stress showed the opposite tendency. Speaking to a complex and differentiated relationship between the desire to know more (state curiosity) and the enjoyment of unfolding music, these two groups did not, however, differ in how curious they reported feeling as a function of the IC of cued events. Indeed, unlike in Study 1, where groups differentiated by theory training differed with regard to sensitivity of their curiosity ratings to the IC-entropy interactions, here the two groups (clustered in terms of their relative curiosity profiles), did not differ in this regard.

Our study provides evidence that trait level differences in how curiosity is experienced (and specifically how the stress of curiosity-inducing information is tolerated) can account for variations in the enjoyment listeners feel (and report) when listening to unfolding music. It was able to do this thanks to the multi-dimensional scale of curiosity (Kashdan et al., 2018) that allowed clustering of listeners based on key ways in which their curiosity profiles differ. Here, it is important to acknowledge that the two clusters that were compared are the result of controlling for overall levels of curiosity, and thus differ primarily with respect to how participants' relative strengths on the five dimensions differ from each other. As such, our clusters may have grouped together previously observed (Kashdan et al., 2018) subgroups of curious people (e.g. Kashdan et al.'s "Problem solvers" who are high in Deprivation sensitivity and "Empathisers" who are high in social curiosity may have been combined into our cluster 1[4]) while splitting others (e.g. the avoiders, who are generally low on all dimensions).

In any case, the cluster solution obtained here (whereby groups differed primarily with respect to stress tolerance) likely captures the primary way in which individuals may differ in terms of their curiosity profiles. Further, comparing the two emergent profiles obtained here is also arguably the most useful way to explore differences in how listeners may enjoy music as a function of the surprise and uncertainty it affords as it unfolds. This because, compared to other dimensions of the 5 dimensional curiosity scale like Social Curiosity or Thrill Seeking, the dimension Stress Tolerance captures precisely how well individuals are able to deal with the stress of the surprising and unknown. Nevertheless, we propose that with richer more complex stimuli, it would be highly relevant to compare how music is responded to and enjoyed by a wider range of curiosity profiles (Kashdan et al., 2018).

General discussion

The last decade has seen an explosion in the use of information theory as a framework for conceptualizing music processing. Music listening, now ubiquitously couched in the

[4] That problem solvers who are high in deprivation sensitivity grouped with the empathisers who are high in social curiosity may be due to the fact that the social curiosity items also tapped into feelings of sensitivity to information that one is deprived of.

language of predictive coding (Koelsch, Vuust & Friston, 2019), would seem to offer a useful model for examining how we make predictions, how these predictive processes guide information seeking states and behaviours, and how such states and behaviours may be rewarded (Kraus, 2020). Over two studies, we put forward and tested the idea that music listening is a good model for investigating both information seeking states and the reward this sometimes afford. Critically, we threw light on the relevance of exploring state curiosity in the context of music listening, showed how this may be experienced differently as a function of one's musical background, and demonstrated the importance of considering trait levels of curiosity experiences when accounting for music-induced enjoyment. In doing so, we advance theoretical understanding, not just of the mechanisms by which music can capture and keep a listener's curiosity and attention, but also by which curiosity and reward may emerge as a function of the interaction between stimulus properties and individual differences.

Information theoretic versus stimulus valence influences on music-induced curiosity as a function of domain expertise.

Despite theoretical and empirical work emphasizing a role of expectation violation in curiosity induction, the extent to which information theoretic properties of music influence felt curiosity had not previously been explored. Our results, showing that the IC and entropy of musical events predict curiosity ratings, are in line with the notion that surprise and uncertainty influence feelings of curiosity (Gottlieb et al., 2013; Kidd & Hayden, 2015). They also extend the existing body of work showing that such events can lead to longer processing times (Omigie et al., 2012), greater arousal in listeners (Egermann et al., 2013; Steinbeis et al., 2006), and greater activation of areas involved in curiosity induction, such as the anterior cingulate gyrus and insula (Omigie et al., 2019a; Omigie et al., 2019b).

The finding in Study 1 (also replicated in Study 2) that the entropy of probed notes has a modulatory influence on curiosity ratings is in agreement with previous studies showing that entropy and specifically, IC-entropy interactions can account for perceptual and emotional responses to musical events. (Hansen & Pearce, 2014; Quiroga-Martinez, et al. 2019 a, b; 2020; Lumaca, et al., 2019; Bianco et al., 2020). Our results thus support the idea that Shannon entropy is a reliable cognitive model of predictive uncertainty, which in turn influences subjective feelings of curiosity.

Further, the finding that those with little to no musical background (no music theory training and largely no experience with an instrument) provided curiosity ratings that were less influenced by information theoretic structure could be considered surprising given that all listeners passively learn the structure of music and may thus be considered latent music experts (Tillmann, Bharucha & Bigand, 2000; Bigand & Poulin-Charronnat, 2006; Pearce, 2018; Rohrmeier, Rebuschat & Cross, 2011). It may also be considered surprising given that previous studies have sometimes failed to find music sophistication/ expertise influences on how entropy modulates neurophysiological responses to prediction errors (Bianco et al, 2019; Quiroga et al., 2019b). However, these findings are not so surprising when considered alongside numerous studies that show a strong influence of musical expertise on musical task accuracy and the strength of neural responses to musical stimuli (Fujioka et al, 2004; Koelsch, et al., 2002a; Tervaniemi, 2009; Vuust et al., 2012; Fujioka et al., 2006). Here we argue that our findings highlight an important role that domain specific expertise may play in everyday experiences of and engagement with music. Indeed, we argue that curiosity ratings from our participants with theory training (and greater experience with playing an instrument) may have shown greater sensitivity to IC and entropy because such listeners are more likely to actively follow the flow of musical structure (Hanslick, 1986), whereas non (theory) trained listeners may experience music in a more holistic way.

Critically, the fact that, in Study 1, the curiosity ratings of both groups were tightly related to the pleasantness ratings given at the end of the melody would seem to provide support for the notion that information seeking is in part driven by stimulus valence (Marvin

& Shohamy, 2016; van Lieshout, Traast, de Lange, & Cools, 2019). That the strength of this relationship was especially high in listeners with no theory training is in line with previous findings showing a tendency for such listeners to make music-related judgments that are largely influenced by emotional responses and evaluations (Müller, Höfel, Brattico, & Jacobsen, 2010).

Accounting for music-induced pleasure using individual differences in trait curiosity.

In addition to once more demonstrating the relevance of exploring state curiosity in the context of music listening, our Study 2 showed the relevance of considering individual differences in trait curiosity (e.g. Litman & Spielberger, 2003; Litman et al., 2005; Kashdan & Silvia, 2009; Grossnickle, 2016; Kashdan et al, 2018), when accounting for the dynamics of enjoyment of unfolding music. Our clustering analysis resulted in two groups differing in their tolerance of stress in the face of high curiosity-inducing stimuli. Importantly, while the two groups did not differ with respect to how curious they reported feeling in response to notes as function of IC (and entropy), the stress intolerant group, in contrast to the stress tolerant group, reported greatest pleasure in response to low IC notes.

Our results corroborate those showing that variations in how pleasure emerges from unfolding musical sounds can be accounted for by the information theoretic properties of these sounds (Cheung et al., 2019). Although we were not able to show the interaction between IC and entropy that was key in the study from Cheung and colleagues, we showed that IC does meaningfully influence enjoyment of heard notes as a function of the trait curiosity profile of the listener. Our results also extend previous findings showing that higher levels of trait curiosity are associated with greater appreciation of novelty in the arts (Fayn et al., 2015). Openness to experience is a trait that is commonly used as a proxy for curiosity at a trait level. However, as it does not differential a general interest in information from the felt valence of experiencing that information, openness to experience, as an operationalization, may lack the sensitivity necessary to delineate aesthetic responses to music. Here we show that enjoyment of information may be separable from a curiosity for that information, and that, specifically, such enjoyment may be explainable by how well stress is tolerated by an individual.

Limitation and implications

Arguably the main limitation of the current studies is their reliance on participants' self-report of their own felt curiosity. However, given that musical stimuli had not previously been used in research into state curiosity, it seemed appropriate and necessary to first evaluate whether participants ratings follow the expected patterns, when participants are asked to describe their experience of music in these terms. We suggest that having provided first evidence that listeners do largely show the hypothesised patterns, and having shown that individual differences in expertise and trait curiosity may play a crucial role, implicit measures of curiosity may now be more confidently employed in the context of music listening paradigms. Specifically, further work studying curiosity in the context of music listening - in the knowledge that such measures may be interpretable in terms of music-induced curiosity- could use waiting time, work expended, memory and pupil dilation (Bianco et al., 2020; Kang et al., 2009), to obtain data that is less susceptible to participant demand characteristics.

Another limitation is our inability to declare precisely which aspects of music background may modulate the degree of influence that information theoretic structure has on curiosity ratings. Not surprisingly, music theory training which we focused on was highly correlated with the number of years of playing an instrument that participants reported, making it difficult to delineate the influence of these different aspects of musical expertise. Future studies could use tools like the Goldsmiths Musical Sophistication Index (Müllensiefen, Gingras, Musil & Stewart, 2014) to characterise listeners, not just in terms of musical training but other dimensions such as active engagement with music and perceptual skills, and in doing so enable precise insights into what aspects of musical background may play a key role.

Last but not least, while findings from Study 1 seem to replicate previous findings showing that stimulus valence influences unfolding curiosity, the fact that pleasantness ratings were requested only at the end of the melodies limits our ability to confirm that curiosity ratings were being influenced by valence judgments rather than the other way around. Similarly our choice of wording for the question inquiring after melody valence, whereby we ask participants how pleasant they had found the melody makes it relatively unclear whether listeners were reporting on how pleasant they *perceived* the melody to be or how pleasant they *felt* it to be. This is an important distinction in the music psychology literature, where it has been shown that felt and perceived emotions are often not the same (e.g. Gabrielsson, 2001). Taken together, we suggest that while the current studies corroborate previous findings of an association between stimulus valence and information seeking states (Marvin & Shohamy, 2016; van Lieshout et al., 2019; Charpentier et al., 2018), further studies are needed to elaborate on such valence – curiosity associations in music listening contexts specifically.

Taken together, our findings – and the field's emphasis on a need for a wider variety of stimuli and methods - recommend the use of musical stimuli in further studies of curiosity. Future studies could harness richer and more complex musical stimuli than we have used here (e.g. Taher, Rusch & McAdams, 2016) in order to provide new insights regarding how curiosity states influence exploratory behaviour. For example, an interesting question is how curiosity may determine the stream of information that an agent will choose to explore when there are numerous streams of information that they could choose from (Dubey & Griffiths, 2020). Paradigms using polyphonic (multi-streamed) music, for example, have the potential to begin to address such questions.

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Author Contributions Statement

JR and DO designed the experiment. JR collected the data. JR and DO analysed the data. JR and DO wrote the manuscript.

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Figure Captions

Figure 1

Musical stimuli and experimental protocol. A) A sample melody and its information content profile. The information content of individual notes in melodic stimuli were estimated using a computational model of musical expectation. B) Participants responses were elicited using a clock whose hand counted down in quarter steps to the 12 O clock position. After hearing the note corresponding to this visual cue, participants indicated how curious they were about how the ongoing melody would continue to unfold. At the end of each melody, participants also indicated how pleasant they found the melody, and whether it was familiar to them.

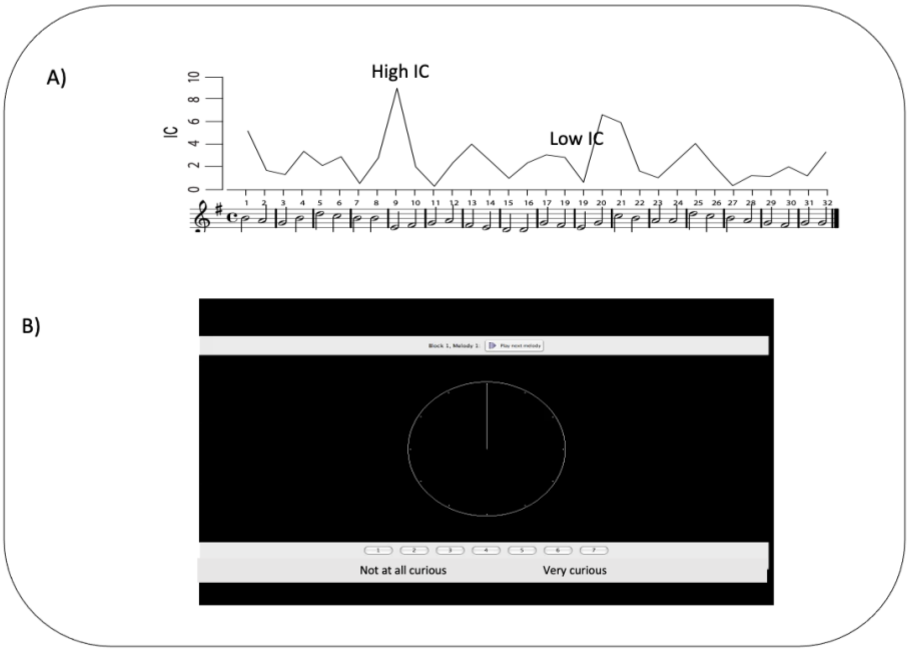

Figure 2

Curiosity ratings as a function of note information content and entropy in the group with musical training. At medium to lower levels of entropy, greater curiosity was induced by high IC notes while the relation between note information content was curiosity was more complex at high entropy levels.

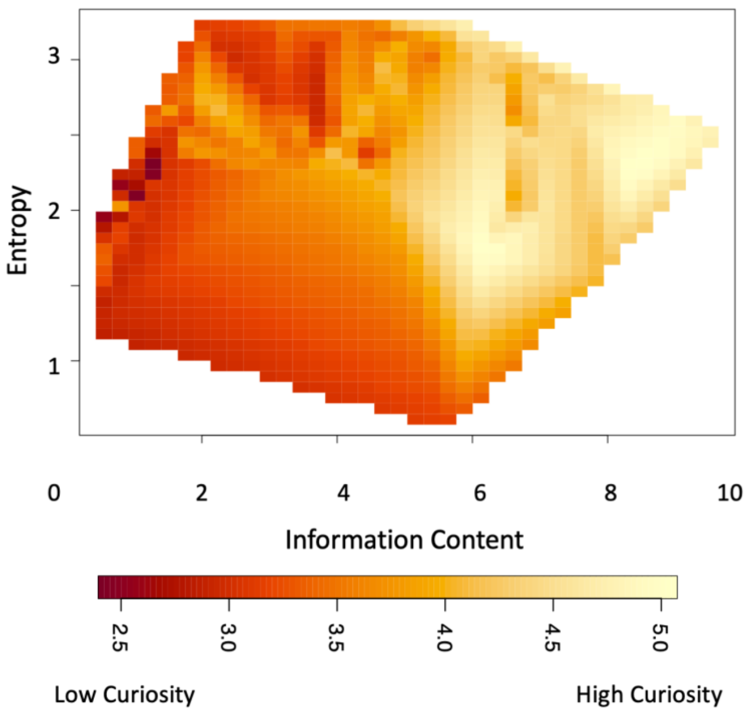

Figure 3

Results of K means cluster analysis splitting participants into two maximally opposed groups based on standardized scores on the 5 curiosity dimensions. Participants primarily differed with respect to their levels of stress tolerance.

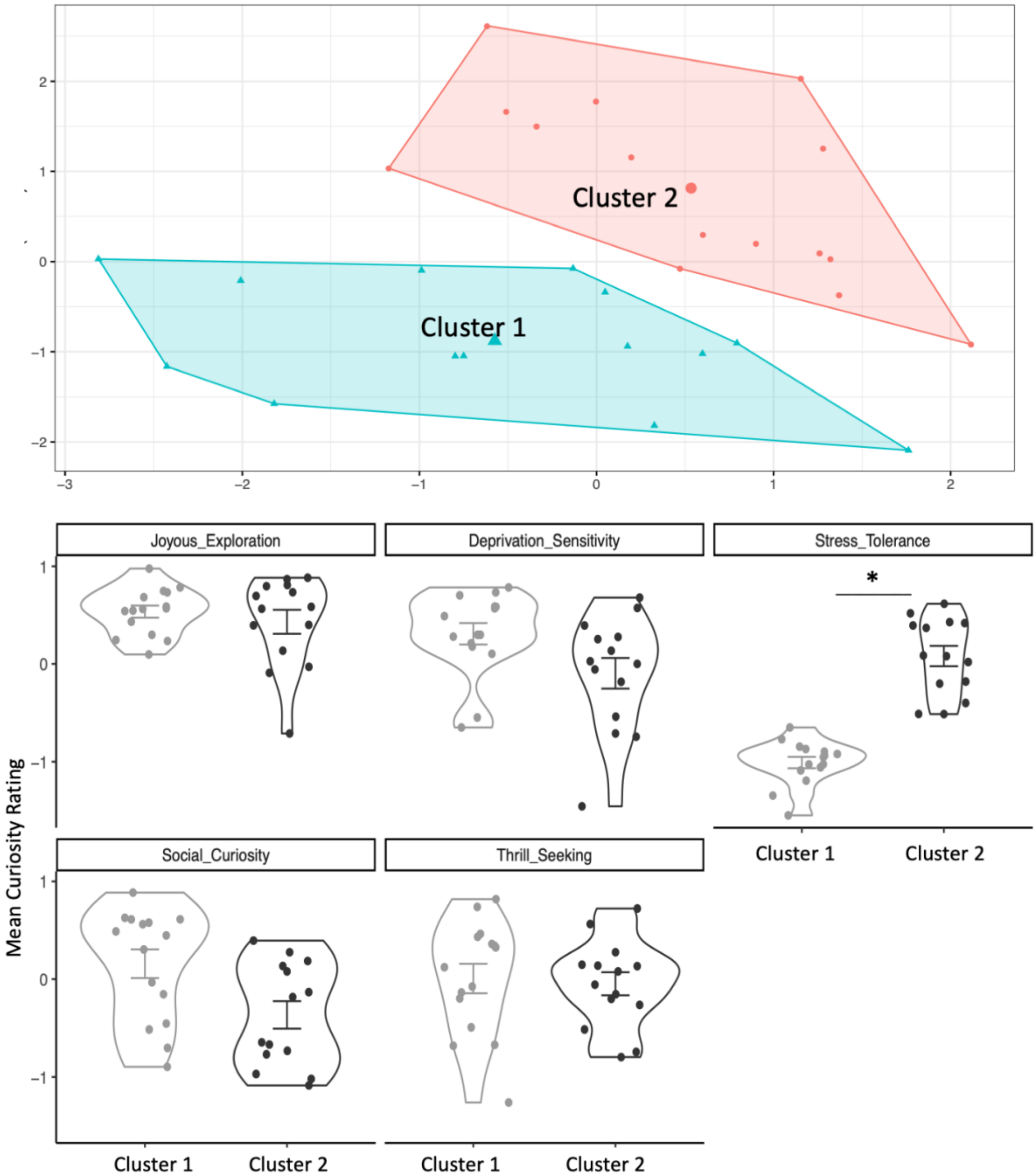

Figure 4

Scatter plots and regression lines showing curiosity and enjoyment ratings as a function of note information content. The stress intolerant and stress tolerant clusters did not differ with respect to the strength of the relationship between note information content and reported curiosity levels. However the stress intolerant cluster demonstrated a negative relationship between note information content and enjoyment ratings while there was a tendency towards a positive relationship in the stress tolerant cluster.

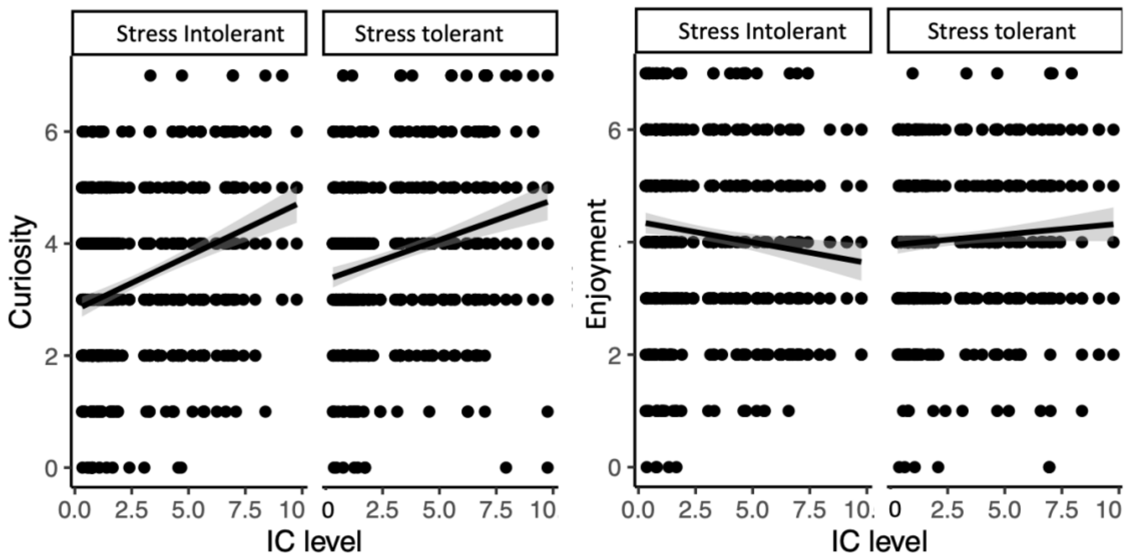

Table 1

Results of linear mixed models examining effect of Note information content, Note entropy and Musical training on Curiosity ratings

	Parameter estimates					Confidence intervals	
Variable	**Estimate**	**SE**	**df**	**t**	**p**	**LL**	**UL**
(Intercept)	2.85	0.31	394.09	9.07	0	2.23	3.46
Information content	0.09	0.07	1917.33	1.4	0.161	-0.04	0.22
Entropy	0.21	0.12	1826.1	1.72	0.085	-0.03	0.44
Music Training	0.77	0.43	367.3	1.79	0.074	-0.07	1.61
Information content x Entropy	-0.03	0.03	1736.63	-1.02	0.306	-0.08	0.03
Information content x Training	-0.06	0.09	3363.31	-0.71	0.479	-0.24	0.11
Entropy x Training	-0.52	0.16	3363.31	-3.25	0.001	-0.84	-0.21
Information content x Entropy x Training	0.1	0.04	3363.31	2.67	0.008	0.03	0.18

Table 2

Results of linear mixed models examining effect of Note information content and Note entropy on Curiosity ratings for the theory trained and non theory- trained participants separately.

		Parameter estimates					Confidence intervals	
Participant group	Predictor	**Estimate**	**SE**	**df**	**t value**	**p**	**LL**	**UL**
Theory Training	(Intercept)	3.48	0.31	237.44	11.08	0	2.87	4.1
	Information content	0.05	0.07	613.31	0.79	0.43	-0.08	0.19
	Entropy	-0.25	0.12	593.86	-2.01	0.05	-0.49	-0.01
	Information content x Entropy	0.06	0.03	545.43	2.03	0.04	0	0.12
No Theory Training	(Intercept)	3.03	0.33	185.6	9.15	0	2.38	3.68
	Information content	0.06	0.07	998.25	0.84	0.4	-0.08	0.19
	Entropy	0.11	0.13	916.9	0.88	0.38	-0.13	0.36
	Information content x Entropy	-0.01	0.03	899.43	-0.36	0.72	-0.07	0.05

Table 3

Means, standard deviations, and correlations with confidence intervals of the five z-scored curiosity dimensions used to cluster participants.

Variable	*M*	*SD*	Joyful Exploration	Deprivation Sensitivity	. Stress Tolerance	Social Curiosity
Joyous Exploration	0.49	0.36				
Deprivation Sensitivity	0.11	0.54	-.14 [-.48, .24]			
Stress Tolerance	-0.48	0.63	-.09 [-.44, .29]	-.49** [-.72, -.15]		
Social Curiosity	-0.10	0.60	-.09 [-.44, .28]	-.26 [-.58, .11]	-.37* [-.65, -.01]	
Thrill Seeking	-0.02	0.51	-.34 [-.63, .03]	-.05 [-.41, .33]	-.23 [-.55, .15]	-.37* [-.65, -.00]

Note. M and *SD* are used to represent mean and standard deviation, respectively. Values in square brackets indicate the 95% confidence interval for each correlation. The confidence interval is a plausible range of population correlations that could have caused the sample correlation. * indicates $p < .05$. ** indicates $p < .01$.

Table 4

Descriptive statistics and between subject t-tests comparing the two clusters on the five dimensions of curiosity.

	Cluster 1		***Cluster 2***			***T tests***	
Curiosity dimension	***M***	***SD***	***M***	***SD***	***t***	***df***	***p***
Joyful Exploration	0.53	0.23	0.43	0.46	0.78	27	0.44
Deprivation Sensitivity	0.30	0.42	-0.1	0.59	2.14	27	0.04
Stress Tolerance*	-1	0.22	0.08	0.39	-9.11	20.52	<0.001
Social Curiosity	0.16	0.57	-0.37	0.52	2.57	27	0.02
Thrill Seeking	0.01	0.59	-0.05	0.42	0.28	27	0.78

*Note: *A t-test for groups with unequal variance was used for the Stress Tolerance dimension after a Levene Test of Homogeneity of Variance indicated unequal variance across groups for this dimension.*

Table 5

Results of linear mixed models examining effect of Note information content and Curiosity group on Curiosity and Enjoyment ratings

		Parameter estimates					Confidence intervals	
Dependent variable	**Predictor**	**Estimate**	**SE**	**df**	**t**	**p**	**LL**	**UL**
Curiosity	(Intercept)	2.83	0.19	38.32	14.75	<.001	2.45	3.2
	Information content	0.19	0.02	881.51	8.63	<.001	0.15	0.23
	Curiosity group	0.52	0.27	35.82	1.93	0.06	-0.01	1.05
	Information content x Curiosity group	-0.05	0.03	1174.52	-1.49	0.14	-0.1	0.01
Enjoyment	(Intercept)	4.36	0.22	32.51	19.46	<.001	3.92	4.8
	Information content	-0.08	0.02	912.92	-3.91	<.001	-0.11	-0.04
	Curiosity group	-0.41	0.32	31.48	-1.27	0.21	-1.03	0.22
	information content x Curiosity group	0.11	0.03	1178.89	4	<.001	0.06	0.16