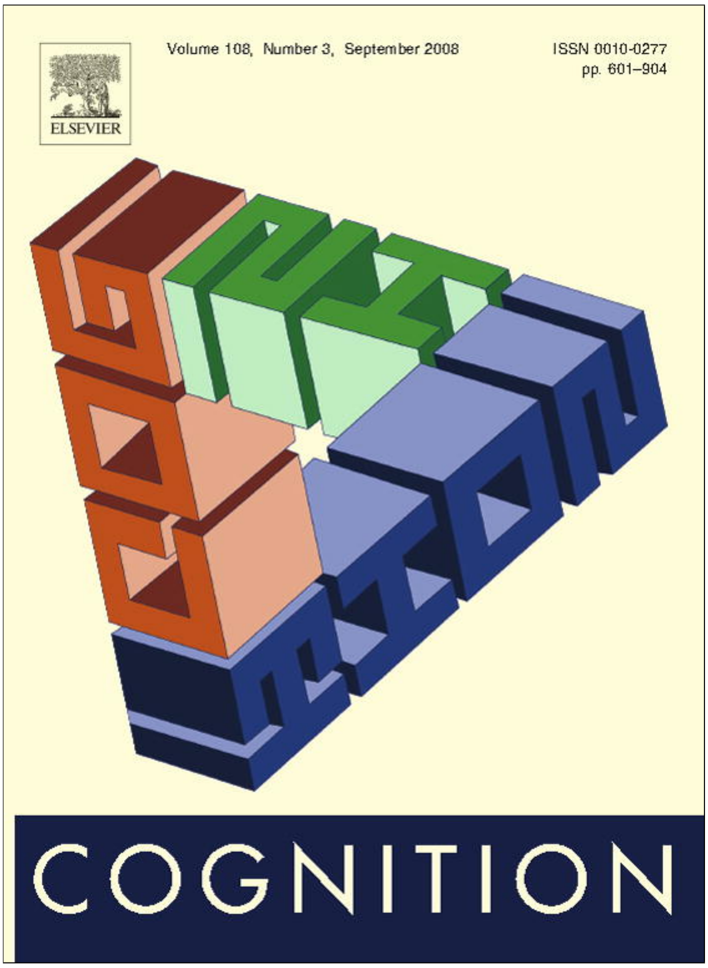
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Cross-modal interactions in the experience of musical performances: Physiological correlates

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ABSTRACT

This experiment was conducted to investigate cross-modal interactions in the emotional experience of music listeners. Previous research showed that visual information present in a musical performance is rich in expressive content, and moderates the subjective emotional experience of a participant listening and/or observing musical stimuli [Vines, B. W., Krumhansl, C. L., Wanderley, M. M., & Levitin, D. J. (2006). Cross-modal interactions in the perception of musical performance. Cognition, 101, 80–113.]. The goal of this follow-up experiment was to replicate this cross-modal interaction by investigating the objective, physiological aspect of emotional response to music measuring electrodermal activity. The scaled average of electrodermal amplitude for visual–auditory presentation was found to be significantly higher than the sum of the reactions when the music was presented in visual only (VO) and auditory only (AO) conditions, suggesting the presence of an emergent property created by bimodal interaction. Functional data analysis revealed that electrodermal activity generally followed the same contour across modalities of presentation, except during rests (silent parts of the performance) when the visual information took on particular salience. Finally, electrodermal activity and subjective tension judgments were found to be most highly correlated in the audio-visual (AV) condition than in the unimodal conditions. The present study provides converging evidence for the importance of seeing musical performances, and preliminary evidence for the utility of electrodermal activity as an objective measure in studies of continuous music-elicited emotions.

1. Introduction

The scientific exploration of music perception and cognition has enjoyed exponential growth in the past few decades (Levitin, 1999) and follows a long and distinguished history dating back to the origins of experimental psychology/psychobiology. The Gestalt psychology movement, for example, was vitally concerned with questions about the nature of melody and melodic transformations (Ehrenfels, 1890/1988), and Wundt, Fechner and Helmholtz devoted a great deal of their research to understanding fundamentals of sound (Boring, 1942). The vast majority of human experiments conducted over the past century have focused primarily on psychophysical, perceptual and cognitive aspects of music, with comparatively little time devoted to studying the emotionally expressive aspects of music (Vines, Krumhansl, Wanderley, Dalca, & Levitin, 2005). Given that music serves to communicate emotion (Bernstein, 1959/2004; Meyer, 1956; Meyer, 1994; Schopenhauer, 1859), this represents an unfortunate bias in the history of the field, but one that is being remedied as emotion has recently become a major topic of study for experimental psychology in general (Adolphs, 2002; Elfenbein & Ambady, 2002; Izard, 1992), behavioral neuroscience (Davidson, Jackson, & Kalin, 2000) and music cognition

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specifically (Juslin & Laukka, 2003; Krumhansl, 2002; Levitin, 2006; Vines, Krumhansl, Wanderley, & Levitin, 2006). We begin this paper with two fundamental questions about musical representations in humans: first, to what extent are listeners sensitive to the expressive intent of composers; and second, how do people integrate information from the visual and auditory domains when experiencing a musical performance?

Within the field of cognitive neuroscience, psychophysiology has been shown to be a powerful tool for understanding complex cognitive, behavioural and affective states or events, an objective measure that can be used alongside or in lieu of subjective measures (Hugdahl, 1995; Lang, 1968; Sutton, Braren, Zubon, & John, 1965; Tranel & Damasio, 1985). Music offers a promising avenue for investigating the physiological correlates of emotions, especially given that most people report the main function of music in their everyday lives is the regulation of their mood through music-induced changes in emotional states (North, Hargreaves, & Hargreaves, 2004; Sloboda, 1999). Two opponent views exist with respect to musical emotions: cognitivism and emotivism. The supporters of cognitivism argue that music does not produce emotions in listeners, but that it merely represents emotions that are recognized, but not experienced by the listeners (Meyer, 1956). In contrast, the emotivist theory claims that music does elicit emotional responses in listeners (Iwaki, Hayashi, & Hori, 1997; Krumhansl, 1997). Given the potential biases in verbal subjective self-reports and the lack of consensus on an operationalized definition of emotion, Scherer and Zentner (2001) argued that it is difficult to find evidence that music not only expresses but also elicits emotion. The measurement of psychophysiological responses to music is an attempt to demonstrate that music does cause bodily reactions and that the latter can be linked to different aspects of emotions experienced while listening to music. In fact, the 100-year-old literature on the study of different responses of the autonomic nervous system, such as cardiovascular activity, body temperature and skin conductivity to music demonstrates that music does have an effect on these measures, but that they vary widely across studies and participants depending on hypotheses and stimuli being tested (see the review by Bartlett, 1996).

Musical experience may be characterized as an ebb and flow of tension that gives rise to emotional responses (Krumhansl, 2002; Meyer, 1956; Patel, 2003; Vines et al., 2006). Many structural features of music contribute to the experience of "tension," including pitch range, loudness dynamics, note density, harmonic relations, and implicit expectations based on experience with a musical genre (Bigand & Parncutt, 1999; Krumhansl, 1996; Meyer, 1956); for this reason, tension is considered a "global" attribute of musical experience (Madsen & Fredrickson, 1993).[1]

Some studies have shown that the intended basic emotions of a musical piece can be identified correctly by listeners. For instance, Krumhansl (1997) selected musical stimuli to represent three distinct basic emotions (happiness, fear and sadness). Participants were instructed to rate continuously the degree to which they experienced one of the three emotions or tension during the performance. Results indicated that continuous ratings of the consistent emotion for each excerpt were significantly higher than for the other emotions. This suggests that music has the potential to produce emotions similar to basic real life emotions and that they are assigned consistently across individuals during a performance.

Moreover, in the second part of Krumhansl's experiment, the physiological changes in the peripheral nervous system were measured in an independent group of participants during the presentation of the same musical excerpts, by tracking heart rate, skin conductance, finger temperature, blood pressure and respiration. Analyses showed that music compared to silence had a significant effect on all the physiological measures recorded. The different selected emotions caused different physiological changes in participants, with larger changes in the sadness and fear music groups. For example, the average skin conductance level decreased the most during the sad excerpts and was highly correlated with average (subjective) sad ratings.

Others have suggested that music-induced emotions are not analogous to primary emotions, but constitute distinct types of emotions that lack verbal labels and definitions (Scherer & Zentner, 2001). For instance, Panksepp (1995) suggested that such emotional responses to music could be defined as 'chills', that is, prickly skin responses similar to shivers ("goosebumps" or "gooseflesh"). He found that up to 0.5 chills/min/person could be elicited while listening to a familiar piece of music, selected for its emotionally moving capacity. The physiological changes occurring during music-induced chills mainly consist of an increase in levels of galvanic skin response and pilo-erection (Craig, 2005). The neural correlates of such chill responses to emotional music have been mapped to brain circuitry involved in pleasant emotion and reward, including increases in nucleus accumbens and ventral tegmental area activity (Menon & Levitin, 2005) and decreases in amygdala activity (Blood & Zatorre, 2001).

As in the mainstream emotion domain, the two main dimensions mentioned in the literature specific to music–emotion are evaluation (or valence) and activity (or arousal; Schubert, 2001). The former varies on a continuum from negative to positive, whereas the latter varies from low to high. Consistent with the findings from pictorial stimuli (Lang, Greenwald, Bradley, & Hamm, 1993), an experiment demonstrated that the arousal dimension of music was associated with autonomic responses, with increases in skin conductance and heart rate associated with higher levels of arousal. On the other hand, the negative and positive valence effects could be associated with electromuscular activity of the corrugator and zygomatic facial muscles, respectively (Witvliet, 1998). Therefore, the study of the physiological correlates of music-generated emotions within these two dimensions of affect seems to be the most appropriate, given our current level of knowledge.

[1] This paragraph was taken verbatim from Vines et al. (2006), p. 83.

The finding that facial muscular activity is related to musical emotion suggests the possibility that these facial muscles might be responding through a mechanism analogous to the "motor theory" of speech perception (Liberman, 1982), a mechanism by which facial muscles react in sympathy to the muscles that were presumed to be used in creating the musical emotion; such a mechanism would parallel the so-called "mirror neuron" system (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996) by which the visual perception of many gestural movements causes corresponding motor neurons to fire (Dimberg & Thunberg, 1998; Levenson, Ekman, & Friesen, 1990). This raises the intriguing possibility that the visual perception of a musical performance (replete with physical gestures) might elicit physiological activity in addition to activity elicited by strictly auditory presentation. This could account for the fact that many people place a high value on seeing musical performances (in concerts, television, etc.) in addition to hearing them (Vines et al., 2005; Vines et al., 2006).

When a music performance is experienced through both auditory and visual channels, these two modes are likely to interact in order to give rise to the emotional experience. Scherer and Zentner (2001) argued that one of the main factors determining the emotional response to music is the performance features, specifically the ability and performance state (i.e. stage presence, motivation, mood) of the performer. This is consistent with findings on paralinguistic cues and the hand gestures that often accompany verbal speech to amplify, modify, or enhance the speech code (McNeill, 1992).

The literature indicates that vision conveys substantial information about internal states and emotions of human gestures. For example, observers are able to detect the covert mental dispositions and intentions of an actor who is performing different movement patterns (Runeson & Frykholm, 1983). Movements of dancers also carry information about both the emotional and structural qualities of the music (Krumhansl & Schenck, 1997). In that study, participants either only heard (AO), only saw (VO) or both heard and saw (AV) Balanchine's ballet of Mozart's Divertimento No.15; they made continuous judgments about the amount of tension and emotion expressed in the ballet during the stimulus presentation. In the three conditions, continuous judgments of tension and emotion correlated strongly, suggesting that amount of tension can be used as a measure for the amount of emotion expressed. For both tasks, the additive combination of the data of AO and VO conditions could predict the AV condition results. Even though AO contributed more to the multiple correlation than VO and the profiles of AO condition as regard to the emotional aspect of the piece were more sensitive and showed greater variability than VO, this study demonstrated that visual information conveys a portion of the affective qualities of music.

On this basis, one might hypothesize that intentional expressivity could be detected as well in the gestures of a solo musician performing a piece. Indeed, it has been shown that observers could correctly identify the emotional intention of soloists who were instructed to play different pieces with three particular performance manners reflecting varying levels of expressivity: "deadpan" where the expression is minimized, "projected" as if playing in front of a public audience and "exaggerated" where the expression is maximized (Davidson, 1993). In that study, the excerpts were presented in three different modes: AO, VO and AV, with the visual stimuli being presented with the Point-Light Technique. This technique, adapted from Johansson's (1973) biological motion technique, consists in creating a high brightness contrast between the major body joints of the actor and the background, so the participant's judgements are based only on movement. It is designed to overcome the possible confounding effects of contextual information of the visual stimulus (such as facial expressions, gender of participant, etc.). Post hoc tests on the manner by mode interaction showed that the VO mode received the most extreme scores while the AO mode received the most moderate scores, indicating that expression conveyed visually was more informative of manner. This finding suggests that movements of musicians reveal their expressive intentions in their interpretation of a piece.

In an attempt to quantify musician's movements, Wanderley (2002) tracked the ancillary gestures of four clarinettists who were instructed to play segments of Stravinsky's second piece for solo clarinet in three ways: standard, exaggerated and immobile. (Ancillary gestures are those movements made while playing an instrument, but that are not necessary for sound production.) They were analysed according to their mode of production, repeatability and degree of similarity across different performers. Movements across players showed substantial differences with regard to the amplitude and temporal characteristics, yet, some performers shared similarities in their movements over time, suggesting an influence of the piece's structure on gesture. For all the players, there was also a tendency to perform similar movements when breathing. This indicates that material and physiological aspects of the performance give rise to similar movements in different players. Finally, within a performer, movements tended to be similar and repeatable, suggesting that they are not spontaneous. It was also found that facial expressions and head movements of singers correlate with the size of sung pitch intervals, suggesting that pitch relation is another structural aspect of music having an influence on the visual aspect of performance (Thompson & Russo, 2007).

Vines and colleagues (2006) studied judgments of both emotion (indexed by perceived tension) and structure (indexed by perceived phrasing) of the performances previously described (Wanderley, 2002). Thirty musically-trained participants were divided into three groups that either only heard (AO), only saw (VO) or both heard and saw (AV) the piece performed by two different musicians (R and W). Participants were instructed to continuously rate the amount of tension or their perception of phrasing experienced during the performance by moving a slider in real time. The experiment found that during specific portions of the piece, vision was more important to the overall experience of tension and phrasing than was sound, and at different points in the piece the opposite held. Moreover, the experience of emotion and structure in the integrated, AV condition was rated more highly than the sum of the

AO or the VO conditions, suggesting an emergent property of experiencing the two modalities together. This finding suggests that the two sensory modalities interact in order to create the overall emotional response.

A logical extension of the experiment conducted by Vines and colleagues (2006) would be to investigate the physiological correlates of these emotional responses as a function of cross-modal interactions, to complement the previously obtained subjective measures with objective ones. In the music–emotion domain, electrodermal activity (or EDA) is a better indicator than other physiological measures (such as heart rate and facial electromyography) of the arousal dimension of emotion (Witvliet, 1998), thus the present experiment employed EDA as the dependent variable. The present experiment constitutes a preliminary investigation of the neurophysiological correlates of musical emotion, as indexed by EDA, with an emphasis on the ways in which two different sensory modalities convey that emotion: vision and audition.

2. Methods

2.1. Experimental design

This study had one between-subjects independent variable: the sensory modality in which the musical performance was presented to the participants. Participants were randomly assigned to one of the three following conditions: they either only heard (auditory only, or AO), only saw (visual only, or VO) or both heard and saw (auditory and visual, or AV) the musical performance. Both prior to the experiment (to establish a resting baseline) and then as the musical performances unfolded, the electrodermal activity of the listeners was continuously recorded as a quantitative measure of the autonomic nervous system activity, or arousal level.

2.2. Participants

Twelve right-handed females between 20 and 25 years of age (mean 22.3 years, SD 1.2) volunteered as participants in this experiment. The participants were required to be musically trained for at least five years. The motivation for this was the observation that using musicians in music perception experiments typically reduces measurement variability without limiting generalizability of the results (Krumhansl, 1991). It has been shown previously that music students exhibit more consistent emotional arousal and more pronounced sympathetic activity (e.g. higher eletrodermal response peaks) while listening to music than non-music students (VanderAck & Ely, 1992; VanderAck & Ely, 1993), thus reducing the signal to noise ratio in the dependent variable.

In the present study, the average amount of musical training of the participants was 9.5 years (SD 4.2). There was no significant difference in years of musical training between the three modality groups ($F(2, 9) = 0.590$, $p > 0.1$). The participants were selected from the same subject population as those in the tension judgement study (Vines et al., 2006). The reason for recruiting different participants instead of collecting new data with the former participants was to prevent any bias due to prior exposure and reaction to the musical stimuli. Therefore, the recollection of previous tension judgments and motor responses to the musical performance would not contaminate the affective experience and physiological measures in the present experiment.

All procedures of this experiment followed the McGill University Policy on the Ethical Conduct of Research Involving Human Subjects and received an approval from the Research Ethics Board – II.

2.3. Materials

2.3.1. Stimulus presentation

The stimuli consisted of three videos[2] of a male professional musician performing Stravinsky's second piece for solo clarinet. These performances were originally created for the study conducted by Wanderley (2002) and later used by Vines et al. (2006). The durations of the three videos were 75 s, 79 s and 80 s. Because this piece is not well known by the general population, it is a good candidate for an experiment in which we want to prevent bias due to previous exposure or to cultural background. This piece was selected in order to compare the physiological responses obtained in the present experiment with the behavioural ratings of different participants for the same musical piece (Vines et al., 2006). The performances were presented using QuickTime software on a Toshiba 15-inch laptop computer screen running Windows NT, an LCD/TFT display with 2048×1536 pixels resolution and 32 bits color depth. The participants in the AV or AO conditions listened to the different performances over Sony MDR-P1 headphones. For consistency across conditions, participants in the AO condition were asked to keep their eyes open and to fixate on the black screen of the laptop while they listened to the musical piece. Participants in the VO condition wore the same headphones during the stimulus presentation, but no sound was produced. At any time during the experiment, the participants in the AO and AV conditions were able to adjust the volume to a comfortable level.

2.3.2. Recording of electrodermal activity

The participants' electrodermal activity was processed with a PowerLab®/4SP high-performance system [ADInstruments Pty Ltd., Colorado Springs, CO]. EDA was measured by applying an alternating current (AC) through dry electrodes (MTL116F GSR Finger electrodes) that were

[2] The three different performances represent the same piece played with different levels of expressivity by the musician: "immobile" where the musician tries to move as little as possible (I), "standard" as if playing in front of a public audience (S) and "exaggerated" where the musician was instructed to maximized his gestures (E). In the original design of this study, this additional within-subject factor, *performance manner*, was included, meaning that all participants were exposed to all three particular performances varying in levels of expressivity. However, during data analysis, only half of the total trials were retained (refer to Result section), which would have resulted in important loss of statistical power for the analysis of performance manner factor. Since the retained trials were evenly distributed across performance manners and since the difference in scaled electrodermal amplitude did not significantly differ between the different manners ($F(2, 14) = .218$, $p = 0.81$), we decided to ignore this factor in the analyses.

attached to the participants' fingers. The amplifier (ML116 GSR Amp) used was fully isolated with low voltage, 75 Hz (~22 mV) AC excitation. Even though electrodermal activity is normally recorded using direct current (DC), AC was applied in this study, as it presents some advantages over DC including the prevention of electrode and skin polarization (Schaefer & Boucsein, 2000). The EDA signal was recorded at a sampling rate of 100 Hz with the software Chart v5 for Windows® [ADInstruments Pty Ltd., Colorado Springs, CO].

2.3.3. Music questionnaire

A modified version of the Queens University Musical Experience questionnaire (Cuddy, Balkwill, Peretz, & Holden, 2005) was completed by the participants. In addition to general information questions, this standard questionnaire includes 20 questions about the music training and background of the participants.

2.4. Procedure

After the signature of the consent form, participants washed and dried their hands and removed watches and jewelry from their left hand. They entered the lighting and temperature controlled testing room equipped with the recording apparatus and stimulus laptop. Participants were invited to sit down in front of the stimulus laptop, and to place their left hand on the armrest of a chair with their palm facing up. They were instructed to keep their hand as still as possible during the whole experiment in order to avoid movement artefacts. The electrodes were then positioned and attached on the palmar surface of that hand, on the middle phalanges of the index and third fingers. The experimenter read the following instructions to the participants:

> *While you are listening to the music, I would like you to focus on the amount of tension you feel in the performance. You can think of tension using any definition you like. We conducted this experiment recently with another group of people who moved a slider up and down to express the tension they experienced during different parts of the performance. While you are listening, I would like you to imagine that you are moving a slider up and down to express the tension you experience in the performance. In your mind, move the slider upward as the tension increases and downward as the tension decreases. Begin with the slider in your mind all the way down, and use the whole range of the imaginary slider.*

The monitor displaying the EDA was hidden from the participants. The participants were then given 3 min to habituate to the sensors and to the testing room in order to obtain a stable electrodermal level. After this relaxation period, the baseline EDA of the participant was recorded for 60 s.

Participants in the three modality conditions (AO, VO and AV) were each exposed to the Clarinet Concerto nine times. The EDA was monitored continuously during the whole experiment, including the 30-s intervals between stimulus presentations. For each performance, only the EDA monitored 10 s before the onset of the performance, during the performance itself and 10 s after the end of the performance was kept for further analysis.

3. Results

Out of the 108 trials recorded (9 trials for each of the 12 participants), 51 trials showed clear evidence of dynamic electrodermal responses during the musical performances, whereas the remaining 57 trials were flat signals with little or no variation (or discrete brief peaks likely representing movement artefacts). The criteria for EDA signals to be retained for analysis were the following: at least two peaks with an amplitude of more than one standard deviation lasting more than 5 s and less than 50 s, or showing a variation in amplitude during the 5 seconds following the onset of the piece. Only the 51 trials meeting these criteria were analysed (the 51 trials retained were representative of the 12 participants). Different statistical techniques were employed in order to fully explore these physiological data: correlation across modalities, analysis of variance and functional data analysis. We also employed a new technique to separate the phasic from the tonic components of the signal (Benedek & Kaernbach, 2008). Finally, EDA data were then correlated with subjective tension data obtained in a previous study by Vines and colleagues (2006).

3.1. Correlation analysis

Correlations of EDA signals between sensory modalities were performed in order to understand the relation between seeing only, hearing only, and both hearing and seeing the performance. The curves representing the average of all EDA signals for each sensory modality were constructed and a correlational analysis was performed between those curves. It yielded correlation coefficients of 0.04 for AO vs. AV conditions, -0.14 for AO vs. VO conditions and -0.01 for VO vs. AV conditions. None of these correlations was found to be significant. Fig. 1 shows the average EDA signal for each modality of presentation. Note that for time-varying data, these Pearson correlations are not considered as statistically powerful as functional analyses which will be reviewed in Section 3.3.

3.2. Analysis of variance

As a first step in the analysis, the average amplitude of electrodermal activity was compared across the three levels of sensory modalities. In order to account for the variability between and within participants in EDA, it is customary to establish a baseline for scaling the EDA data; researchers have used the previous 15 seconds (Gomez & Danuser, 2004) or the previous 5 seconds (Kaszniak, Reminger, Rapcsak, & Glisky, 1999) for this purpose. Here, we took into account baseline activity in the 10 seconds preceding the stimulus epoch. That is, for each trial, the average amplitude of the 10-s baseline activity before the onset of the music was subtracted from the electrodermal amplitudes when music was presented. The resulting values we refer to as the scaled electrodermal amplitudes.

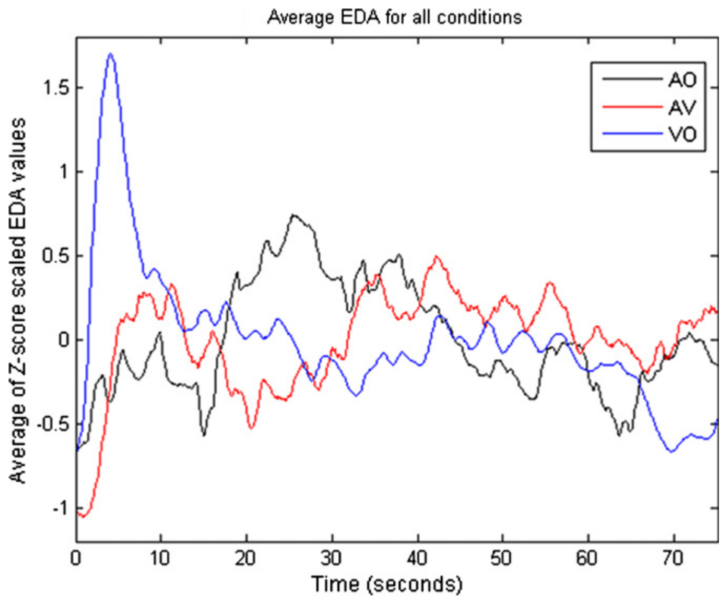

Fig. 1. Average *z*-score scaled EDA curve for each condition (AO, AV, VO) as a function of time (in seconds).

A one-way ANOVA with scaled electrodermal amplitude as the dependent variable and sensory modality as an independent-group factor yielded a significant difference in scaled electrodermal amplitude ($F(2, 48) = 7.51$, $p < .001$) depending on the sensory modality. Scheffé post hoc tests on sensory modalities revealed that EDA amplitude of the AV condition (mean 1.16, SD 1.68) was significantly higher than that of both AO (mean 0.17, SD 0.59; $p < .01$) and VO (mean 0.30, SD 0.85; $p < .01$) conditions. Fig. 2 shows the EDA averaged across all trials as a function of the sensory mode. Single sample *t*-test comparing each group scaled mean to 0 (i.e. no difference between baseline EDA and music EDA) demonstrated that the mean EDA in AO and VO conditions did not significantly differ from baseline EDA ($t(13) = 1.080$, $p > .05$; $t(18) = 1.538$, $p > .05$, respectively), but the mean EDA in AV condition significantly differ from baseline EDA ($t(17) = 3.841$, $p < .01$).

In order to account for between subject variability, a one-way ANOVA was performed to compare scaled electrodermal amplitude between participants for each modality of presentation. There was no significant difference between the subject for each condition ($F(3, 10) = 1.373$, $p > .05$; $F(3, 15) = .538$, $p > .05$; $F(3, 14) = 2.299$, $p > .05$ for AO, VO and AV, respectively), suggesting low between subject variability. No significant correlation was found between average scaled EDA amplitude and years of musical training ($r = -0.174$, $p > .01$).

3.3. Functional analysis of variance

In the analysis of variance reported above, curves of 7500, 7900 and 8000 values (corresponding to 100 values per second collected for the three respective performances) for the signals were collapsed into one single va-

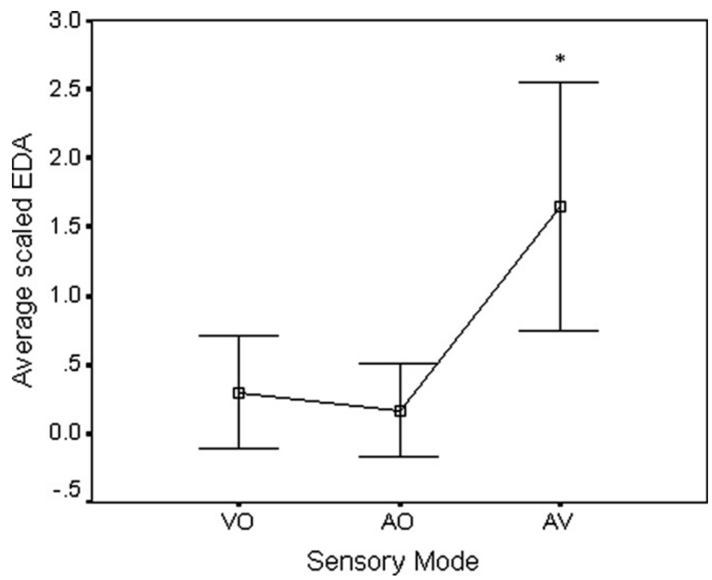

Fig. 2. Overall mean electrodermal amplitude as a function of sensory modality, indicating a main effect ($^{*}p < .001$) of sensory mode, with AV > AO = VO. The error bars represent the standard error of the mean.

lue, which was then compared across conditions. Averaging curves into a single data point results in loss of information about of the dynamics of physiological reaction to music. As both music and EDA vary over time, it is important to capture general patterns and particular events in participants' skin conductance as time unfolds and to relate these events to the musical performance. One way to look at the present data is to consider each set of data (i.e. each trial) as a curve on a time scale instead of a string of independent numbers. The curves can be represented by mathematical functions each of which become a datum, and are analyzed using functional data analysis (Levitin, Nuzzo, Vines, & Ramsay, 2007; Ramsay & Silverman, 2005).

Before these functional transformations were performed, the raw data were downsampled, scaled and time-warped. The initial sets of data comprise 7500, 7900 and 8000 values, that is, 100 values per second. Each set of data was downsampled by a factor 10, resulting in 10 data points per second. As EDA is a slow physiological response (i.e. seconds), one data point per 10th of a second was estimated to be sufficient. Each data set was then scaled in z-scores in order to control for the great variability in absolute values from one data set to another. (This follows because we were not interested in the absolute EDA value, but in its change as a function time.) Finally, because the three different performances presented in all conditions were not of equal duration, the resulting electrodermal activity signals were not all of the same duration within each subject and each modality of presentation. In order to have signals of equal length and of corresponding points in time, the time vectors of the shortest signals (75s and 79s) were stretched to the length of the longest time vector (80s) using time-warping registration. With this mathematical procedure, the idea is to scale, by globally expanding time, the recorded time points for each trial so that it corresponds to time points of a reference time vector, which in this case was the longest dataset (standard performance manner). We performed simple linear transformation of the timings for the shortest signals so they would correspond to the reference timing. In some complex time-warping functions, time is stretched over some intervals and compressed over others. However in this case, we opted for a global stretching approach, which we considered would provide a good approximation of time matching with minimal loss of information about differences in EDA reaction times between modalities of presentation.

Each of these curves was mathematically modeled by using 50 4th order (cubic) B-spline functions. Spline functions are considered best at approximating most non-periodic functional data. Modeling the data with 50 functions, rather than keeping all of the 750, 790 or 800 points as independent parameters rendered our basic units of analysis more computable and allowed for more degrees of freedom in testing the hypothesis and exploring the data. Each functional observation was thus modeled in the form:

$$x_{\mathrm{i}}(t) = \sum_{k=1}^{150} c_k \Phi_k(t),$$

where x is the functional observation (as a function of time), t denotes time, k is the number of basis functions, Φ is a basis function of time, and c is the coefficient corresponding to the basis function.

Three two-way functional analyses of variance (fANOVA) were employed with modality and subjects as the independent-group variable and the random variable, respectively. One fANOVA was employed for each comparison, i.e. AO–AV, AO–VO and AV–VO. One advantage of this technique compared to traditional ANOVA is to allow us to discover when in the musical performance significant differences arise.

3.3.1. AO vs. AV

The electrodermal signals for AO and AV conditions generally followed the same contour, but they differed significantly (DF = 1,6; $p < .05$) from one another between the following sections of the excerpt: 26.4–30.4 s, 39.3–39.5 s, and 58.2–59.4 s. Moreover, using a critical level of $p < .01$, the curves differed significantly during the following sections of the piece: 27.3–9.2 s and 58.6–58.9 s. Fig. 3a shows the F-ratio contrasting these two modalities as a function of time.

3.3.2. AO vs. VO

The electrodermal signals for AO and VO conditions generally followed the same contour, but they differed significantly (DF = 1,6; $p < .05$) from one another between the following sections of the excerpt: 28.1–29.7 s, 35.2–36.4 s, and 38.8–40.2 s. Fig. 3b shows the F-ratio contrasting these two modalities as a function of time.

3.3.3. AV vs. VO

The electrodermal signals for AV and VO conditions generally followed the same contour, but they differed significantly (DF = 1,6; $p < .05$) from one another between the following sections of the excerpt: 1.8–5.1 s, 34.6–39.2 s, 43.1–46.2 s, 73.4–74.1 s, and 77.1–79.1 s. Moreover, using a critical level of $p < .01$, the curves differed significantly during the following section of the piece: 35.3–36.8 s. Fig. 3c shows F-ratio contrasting these two modalities as a function of time.

3.4. Analysis of phasic EDA responses

We also employed a new technique consisting of the decomposition and analysis of single phasic skin conductance responses (Benedek & Kaernbach, 2008). Because EDA reflects a pattern of partially overlapping discrete responses on a slowly changing background, this technique allows distinguishing between the phasic components and a tonic component, and to analyze the amplitudes and onset times of the single phasic responses.

One-way ANOVA showed that the skin conductance response amplitudes were significantly different (F(2, 968) = 53.25, $p < .01$) between the modalities of presentation. Post hoc pairwise comparisons (using Tukey–Kramer's honestly significant difference criterion) revealed that the average of amplitudes in AV mode (mean 0.93 μS, SD 0.97) was significantly higher than amplitudes in AO (mean 0.37 μS , SD 0.40; $p < .01$) and VO (mean

0.49 μS, SD 0.67; $p < .01$) modes. These results are consistent with the differences in average EDA amplitude for the entire signal, as we assessed by ANOVA in §3.2 between the modalities of presentation.

The mean onset times (in seconds) were 9.12, 9.07 and 8.68 for the phasic responses in AO, VO and AV conditions, respectively. One-way ANOVA showed that the onset times did not significantly differ between modalities ($F(2, 968) = 2.73$, $p = 0.07$).

3.5. Correlation with subjective tension judgments

Correlations between EDA and subjective tension data obtained in a previous study (Vines et al., 2006) were performed. The original tension data sets were down-sampled to 10 Hz, resulting in a sampling rate equivalent to EDA data. Each tension data set was then scaled in z-scores in order to control for the great variability in absolute values from one data set to another and to have equivalent scaling and units for tension and EDA data. The curves representing the average of all tension judgments for the same musical stimuli as in the present study were calculated for each sensory modality. A correlational analysis was performed between those tension curves and the average EDA curves for each modality. It yielded correlation coefficients of 0.12 for AO modality and 0.09 for AV modality, which reached significance ($p < .05$; note however that the explained variance is small and the significance is a product of the very large number of datapoints and violations of stationarity). A significant negative correlation coefficient of −0.55 was found between tension and EDA for VO modality ($p < .01$). Fig. 4a, b and c show the averaged curves for EDA and tension in the AO, AV and VO conditions, respectively.

The Stravinsky piece can be regarded as comprising three different sections (Friedland, n.d.). The first section extends from the beginning of the piece to the pause indicated by the double bar (see Appendix A), occurring at $\sim t = 32$ s in the performance we used. The second section extends from the end of Section 1 to the 16th-note rest and breath mark at around 58 s. The third and last section extends from this point to the end of the piece. The first and final sections are similar in musical content, whereas the second middle section is unique. On Fig. 4, these section boundaries are represented by the vertical lines.

Additional correlation analyses between EDA and tension were performed within each of these sections for all three modalities. For the AO modality, correlation coefficients of .32, .07, and .06 were obtained for the first, second and third sections, respectively. For the AV modality, correlation coefficients of .71, .39, and −.63 were obtained for the first, second and third sections, respectively. For the VO modality, correlation coefficients of −.44, .54, and −.90 were obtained for the first, second and third sections, respectively. We performed moving windowed cross-correlations to take into account any lags in latency between the physiological response and the slider responses, and these did not yield significantly different results, so here we report only the correlations on the unshifted data.

Finally, an analysis of variability was performed in order to compare the variance between EDA and tension for each modality. In all AO, VO and AV conditions, variability was significantly greater in the tension judgments than in the electrodermal activity ($F(8, 13) = 7.4$, $p < .001$; ($F(8, 18) = 4.63$, $p < .01$; ($F(9, 17) = 8.90$, $p < .001$, respectively).

4. Discussion

The research described here compliments work on electrodermal response to emotion-evoking stimuli, as well as investigations into the emotional response to musical performance. It also adds new insights into cross-modal interactions giving rise to physiological reactions to music.

4.1. Effect of sensory mode

The higher levels of electrodermal activity for participants who could both hear and see the performances, as compared to those who could only hear or only see, indicates that the interaction between the two sensory modalities conveyed by musical performances created an emergent property, a holistic perception that was greater than the sum of its parts. This result is consistent with the tension study (Vines et al., 2006), which also identified evidence for emergent properties in their AV condition, using subjective behavioral measurements of tension and other emotions. It appears that there is a nonlinear summation of physiological arousal when both sensory modalities are observed. The music theorist, Alexander Truslit, proposed that both a musician's body movements and musical sound originate in the same "inner motion" (*innere bewegtheit*; Repp, 1993). It is important to recognize that all musical sounds, including singing, require movements of the body to produce them. That is, the origin of the auditory signal that we so closely associate with music is in a physical gesture that normally has a visual counterpart. Primates evolved over hundreds of thousands of years in a world in which seeing and hearing one another were part of the same event – indeed, human infants undergo a period of sensory ambiguation in which seeing and hearing are connected (infantile synaesthesia) – and the notion of an audio recording existing independently of the visual gestures that gave rise to the performance is only recent.

Perhaps audience members having access to both dimensions of a performance leads to an enhanced connection with the mental state and musical intentions of the musician, and thus an overall experience with enhanced emotional response. People who enjoy attending live concerts might seek this increased arousal that is not available solely by listening to CDs. It also reveals that the notion that music as a purely auditory art form should be revised to include a visual dimension, since the latter conveys important information about musician's intention and interacts with the sound for the overall arousal state of the listener.

In addition, the present experiment showed that dynamic galvanic skin response was generally similar across the modalities of presentation (AV, AO and VO), that is, the responses tended to follow similar contours. However, in

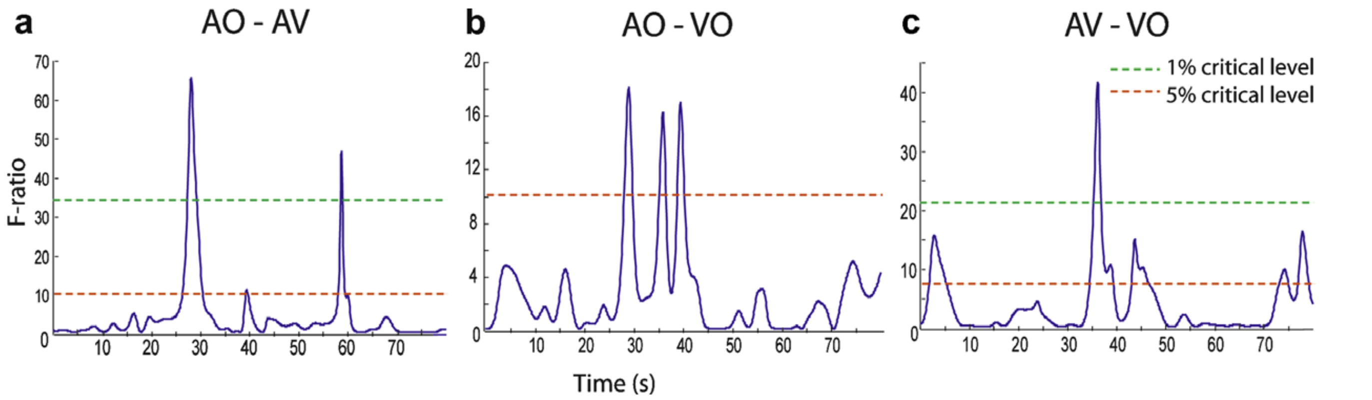

Fig. 3. Functional *F*-ratio for the three pairwise comparisons (a) AO vs. AV conditions; (b) AO vs. VO conditions; (c) AV vs. VO conditions. The green dashed line represents the critical level $p = .01$; and the red dashed line represents the critical level $p = .05$.

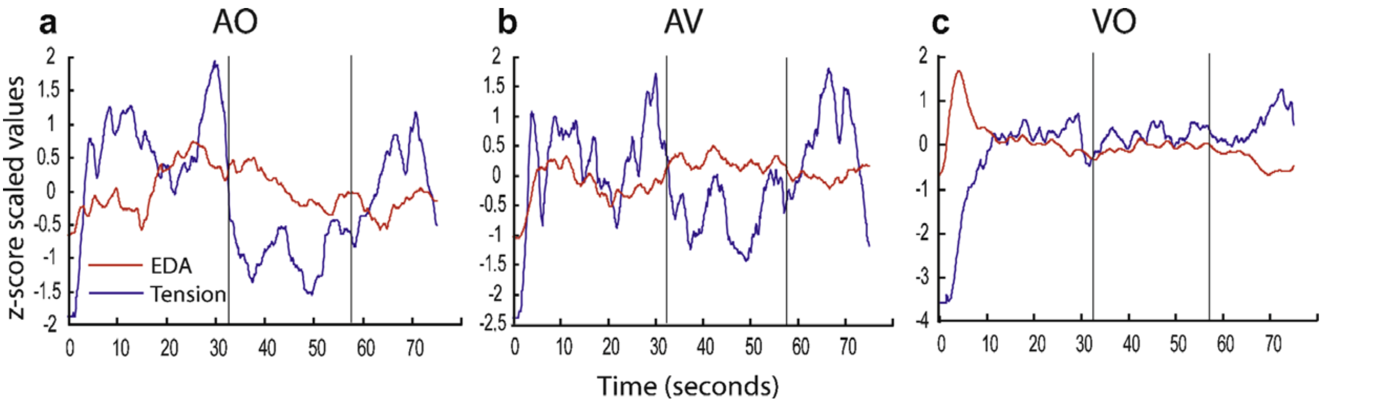

Fig. 4. Average of scaled (*z*-score) values of tension judgments from Vines, Krumhansl, Wanderley, and Levitin (2006) (blue line) and EDA amplitude (red line) as a function of time (a) AO; (b) AV; (c) VO.

some parts of the piece, the level of electrodermal activity varied significantly from one presentation mode to another, revealing its sensitivity to physiological differences, and hence its utility as an objective measure of music-induced emotion. For instance an important musical event occurs between 28 s and 40 s of the piece. At this point, the first section ends at $t = \sim 31$ s and is followed by a long pause before the beginning of the second section at $t = \sim 33$ s. Here there is a discrepancy between the information conveyed in the auditory mode and information conveyed visually. The music stops and a listener unfamiliar with the piece may be uncertain as to whether the piece has ended, or what is going to happen next. An observer of the visual channel has an entirely different informational set available: the performer is holding the clarinet near his mouth, his fingers are at the ready, his eyes are focused on the score and he inhales. The observer in the VO condition is able to extract a great deal of information about what is happening in the piece during this time period, information that is unavailable to the listener in the AO condition. A participant in the AV condition can integrate these two sources of information and appreciate the musical and performance tension that the rest creates.

As we might expect, the electrodermal activity following this musical event is different between modalities of presentation. When the excerpt was presented in the auditory only mode compared with the visual only mode, the electrodermal activity differed significantly at three times points in this time window: from 28.1 to 29.7 s, from 35.2 to 36.4 s, and from 38.8 to 40.2 s. In these portions of the piece, the scaled EDA was higher in the AO condition compared to the VO condition. Electrodermal activity also differed when the musical piece was presented in both modalities (AV) compared with the VO mode from 34.6 to 39.2 seconds (scaled EDA higher in AV than in VO mode) and compared with the AO mode from 26.4 to 30.4 s and from 39.3 to 39.5 s (scaled EDA higher in AO than in AV mode).

As shown on Fig. 5, the average electrodermal activity in the AO condition (black curve) dropped as the first section ended. Then, the performer's breath was closely followed by an increase in EDA levels, probably resulting from a short period of unexpectedness. The EDA levels for participants who only saw the performance (VO) also decreased as the musician stopped moving at the end of the first section. However, the breath preceding the second section was not closely followed by a peak in activity. Instead, the electrodermal activity levels started to increase after the second section had started and the musician started moving again. Finally, during this whole section of the piece, the EDA levels in the AV modality increased with a high amplitude. These results seem to indicate that different modalities conveyed different pieces of information

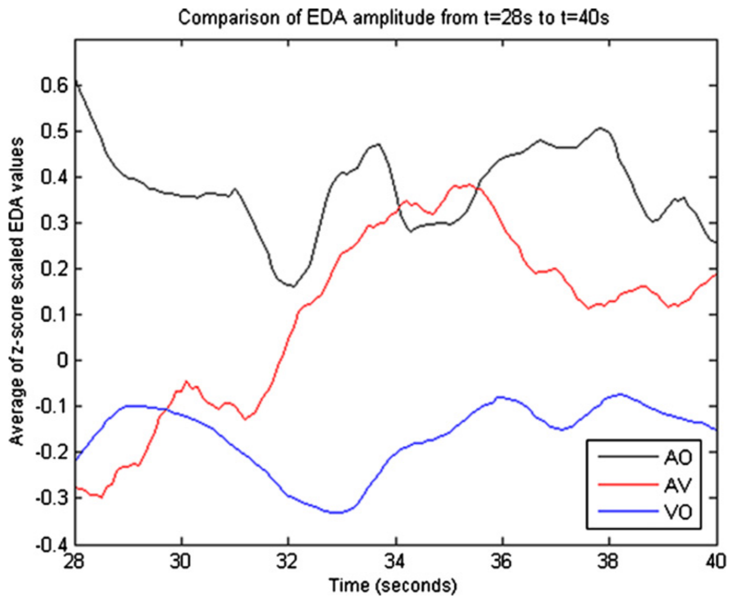

Fig. 5. Average *z*-score scaled electrodermal amplitude as a function of time for each modality condition (AO, VO, AV) for the time window starting at 28 s and ending at 40 s.

about the structure of a musical piece and the tension it expresses, giving rise to different arousal activations measured by electrodermal activity.

Readers interested in knowing more about the direction of the other significant differences yielded by the functional ANOVA can refer to the average EDA curves represented in Fig. 1.

4.2. Comparisons with subjective data

Arousal may be the link between tension and emotionality experienced in reaction to music. Steinbeis, Koelsch, and Sloboda (2006) propose a causal chain whereby the perception of tension in music first leads to increased arousal, which in turn contributes to the subjective experience of emotion. According to this view, any measures of physiological arousal should correlate with continuous tension judgments, and with a small, negative phase offset (that is, occurring occur slightly ahead of time).

Electrodermal activity obtained in our study and the tension judgments (Vines et al., 2006) were indeed found to be positively correlated in some sections of the piece, but also negatively correlated or uncorrelated in other sections of the piece, depending on the modality of presentation and the particular musical events, visual/gestural events or rests taking place. In the AO mode, electrodermal activity and tension judgments were not significantly correlated during the whole piece. When the piece was presented in the VO mode, EDA and tension were significantly negatively correlated during the first and third sections of the piece and significantly positively correlated during the middle section of the piece. In the AV condition (in which both modalities were present), EDA and tension were positively correlated in the first and second sections and negatively correlated in the third section. Based on these results, we can conclude that in some portions of the piece, the electrodermal activity is driven by the same underlying phenomena that are giving rise to the subjective tension judgments. However, this is not true for all portions of the piece. Discrepancies between the two sets of data could be in part explained by the fact that electrodermal activity is a slower response with a more complex dynamics and lower variability over time, or alternatively, that the slider ratings are highly variable and intrinsically subjective. There may be still other factors at work underlying the differences between these two measures – for example, if the discrepancy was merely because EDA is slower, an autocorrelation would have shown up in our sliding window technique.

A correlational analysis of EDA and tension data as sets of functions over time would have revealed more information about the dynamics of the correlation, but no such techniques are available presently (such functional correlations are currently under development in our laboratory and others). This preliminary investigation thus indicates that the hypothesis proposed by Steinbeis and colleagues (2006) may be only part of the story. Factors as yet uncovered may mediate the relationship between tension and physiological arousal, and this will require further investigation.

Finally, the highest correlations between tension and electrodermal activity were found in the condition in which the information was conveyed through both auditory and visual modalities. The integration of the two modalities gave rise to more consistent subjective and physiological responses, suggesting that bimodal integration leads to a better appreciation of the surrounding stimuli and is therefore advantageous. In fact, the integration of multiple sensory channels is also more realistic and naturalistic, as we did not evolve to – and in fact rarely – process information conveyed by only one sense, but tend to perceive, process and react to information presented in a multi-modal fashion.

The idea of measuring subjective tension judgments and electrodermal activity concurrently in the same individuals in our experiment was discarded because of concerns that the movement of the dominant hand for the slider would interfere with the electrodermal activity of the other hand. However, since the participants were instructed to imagine that they were moving a slider up and down to express the experienced tension, it is possible that part of the physiological response was due to motor imagery; a previous study showed that motor imagery and motor behaviour largely share their neural mechanisms (Decety, 2002). Additional experiments in which participants are given no instruction to imagine moving a slider, and in which participants move a slider while their electrodermal activity is being measured in the other hand will help to determine the factors influencing the results identified in the present study.

4.3. Comparisons with musical score

Zones and peaks of tension were determined in the score by a music theorist (A. Vishio, personal communications, April 4, 2003). For instance, he noted a peak of tension at the end of the first section and a zone of tension following the onset of the second section of the piece. At this point in the piece, we observed an increase in average EDA activity in all modes of presentation (Fig. 5) as well as discrepancies in EDA activity across the different modes of presentation. Moreover, the music theorist noted a zone of tension from $\sim t = 65$ s to $\sim t = 68$ s of the musical piece. This section is characterized by a high density of high-frequency notes compared to the preceding section. During this time window, the averaged EDA levels for AO and AV modalities increase, but not for VO modality (see Fig. 1). It is noteworthy that the musician does not perform any high-amplitude movements during this section of the piece. This could explain the non-significant discrepancy between electrodermal activity contour of conditions in which auditory information is available and that of the visual only modality. Some other zones and peaks of tension that have been described by the music theorist do not correspond to changes in average electrodermal activity in the listeners, but tension in the music is not the only factor influencing arousal. Moreover, composers and music theorists may hold incorrect beliefs about what listeners are actually attending to (Lalitte et al., 2004; Levitin & Cuddy, 2004).

Several features in music were pinpointed as causing changes on the arousal dimension of emotion and on some physiological measures. First, expectations are believed to play a great role in musical emotions (Berlyne, 1971; Levitin, 2006; Meyer, 1956; Steinbeis et al., 2006). For instance, increases in the level of harmonic unexpectedness during a musical piece produced increases in subjective tension and emotionality responses as well as in electrodermal activity (Steinbeis et al., 2006). This suggests that a surprising musical structure can increase arousal, but uncertainty (suspense and absence of clear expectations) is also a potential arousal-increasing feature (Berlyne, 1971). This might explain why the breath occurring at $t = \sim 32$ s of the performance caused a peak in electrodermal activity for the auditory, but not for the visual mode of presentation. Other features such as tempo, accentuation and rhythmic articulation, were shown to be highly correlated with physiological measures such as electrodermal activity and could discriminate between high and low arousal (Gomez & Danuser, 2007). Other aspects of musical structure were associated with increased arousal, such as novelty, complexity, ambiguity and instability (Berlyne, 1971).

In the present work, we focused on the dynamic nature of emotional responses to music. The way electrodermal activity varies as a function of time is complex and variable. An important related aspect to be taken into consideration in the following discussion is the latency of EDA, which refers to the interval of time from stimulus presentation to the onset of the physiological response. It usually ranges between 1 and 4 seconds for EDA following the presentation of emotion-evoking stimuli (such as familiar faces (Ellis & Lewis, 2001) and acoustic stimulation (Elie & Guiheneuc, 1990). This is also the latency of EDA following a musical event (Krumhansl, 1996; Sloboda & Lehmann, 2001). Therefore, we estimate the musical stimuli presented in this work to activate physiological responses with a similar time course. Much less is known about the temporal dynamics of latency, that is, whether it is consistent or it varies over time. A better understanding of the dynamics of EDA latency would help determine the temporal relationship between EDA and subjective tension and between electrodermal responses and their underlying events in the musical stimuli.

Our results point to the potential utility of electrodermal recordings as an objective measure to support and further validate subjective judgments of the experience of music-elicited emotions. In fact, electrodermal response reveals the overall affective state of the listener, and especially the arousal dimension of emotional response (Lang, Greenwald, Bradley & Hamm,1993; Witvliet, 1998). At the same time, this study also shows that behavioral continuous measurements convey information that is consistent with objective physiological measures in the experience of emotion.

In conclusion, this research contributes to knowledge about the ties between physiology, subjective emotion, and brain processing of emotion-evoking stimuli and musical performance in particular. Furthermore, it revealed multi-sensory interactions in ongoing perception.

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Appendix A. THREE PIECES FOR CLARINET SOLO, SECOND PIECE

By Igor Stravinsky

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