Acoustic comfort depends on the psychological state of the individual

Martina Lorenzino[a], Flavia D'Agostin[b], Sara Rigutti[c], Massimo Bovenzi[b], Carlo Fantoni[c] and Luigi Bregant[a]

[a]Department of Engineering and Architecture, University of Trieste, Trieste, Italy; [b]Clinical Department of Medical, Surgical and Health Sciences, Clinical Unit of Occupational Medicine, Trieste, Italy; [c]Department of Life Science, Psychology Unit "Gaetano Kanizsa", University of Trieste, Trieste, Italy

ABSTRACT
Recent studies have shown that comfort can be influenced more by psychological processes than from the characteristics of environmental stimulation. This is relevant for different industrial sectors, where comfort is defined only as a function of the intensity of external stimuli. In the present study, we measured physiological and psychological comfort during the exposure to four levels of acoustic noise [from 45 to 55 dB(A)] corresponding to different comfort classes inside a full-scale mock-up of a cruise ship cabin. We found an increase of psychological and physiological discomfort for higher noise intensities, but not for all the intensities defining the comfort classes. Furthermore, we found that negative psychological states determine a lower physiological sensitivity to acoustic noise variations compared to positive states. Our results show that, at normal/low intensities, psychological processes have a greater role in determining acoustic comfort when compared to the stimulus intensity.

Practitioner Summary: This study shows that psychological factors can be more relevant in determining acoustic comfort inside a ship cabin than the intensity of acoustic stimulus itself. This finding suggests that the cruise industry should consider not only the engineering measurements when evaluating comfort on board, but also the passenger' psychological state.

Abbreviations: AIC: akaike information criterion; CCT: colour correlated temperature; cd/m^2: candela/square meters; df: degrees of freedom; F-test: Fisher's test; HF: high frequency; HR: heart rate; HRV: heart rate variability; HSV: hue saturation value; K: kelvin; LF: low frequency; LF/HF: low frequency to high frequency ratio; *lme:* linear mixed effects; ms: milliseconds; nu: normalized unit; p: p value; pNN50: percentage of adjacent pairs of normal to normal RR intervals differing by more than 50 milliseconds; r^2: coefficient of determination; r_c: concordance correlation coefficient; RMSSD: square root of the mean normal to normal RR interval; SD: standard deviation; SDNN: standard deviation of normal to normal RR intervals; SEM: standard error of the mean; t-test: student's tests; χ^2: chi-square test

Accepted 24 July 2020

KEYWORDS
Acoustic noise; heart rate variability; comfort; mood; Weber's law

1. Introduction

Considering the increasing competition in the cruise sector, the customer satisfaction is becoming one of the main topics of interest to the ship owners. In the transport and tourism industry, the study of comfort is gaining importance since a comfortable experience on board of ship, or aircraft, can determine the future passengers' choice of that airline or naval company. In the ship cruise sector, this relevance is reflected in the outbreak of comfort classes definition by different naval Classification Societies. The application of comfort classes is a very important contractual point, subject to penalties when the ship does not fulfil the expected requirements (Blanchet 2000).

In the last years, the notion of comfort has changed and comfort has been studied both in terms of physiological reactivity to environmental stressors, and in terms of cognitive process, where psychological, cultural and social factors interact, determining the comfort experience (Cole et al. 2008; Ortiz, Kurvers, and Bluyssen 2017). Interestingly, recent studies have found that psychological changes, associated to different emotional states, can influence the physiological response to environmental stressors, modifying the

CONTACT Luigi Bregant bregant@units.it Department of Engineering and Architecture, University of Trieste, Via Alfonso Valerio 6/1, 34127, Trieste, Italy

comfort judgments (Wang and Liu 2020). According to these studies, the physiological sensitivity to different stressor levels varies as a function of the individual's emotional state. These findings are particularly relevant since they show that comfort perception is more influenced by the psychological characteristics of the individual than the immediate environmental conditions.

Our study investigates the comfort perception during the exposure to acoustic noise inside a ship cabin. Acoustic noise is one of the main sources of environmental disturbance on board, and today there is no harmonisation between the different Classification Societies about the acoustic noise intensities defining the limits of comfort classes (Scarinzi, Bregant, and Biot 2018). Furthermore, the role of human factor in defining comfort thresholds is completely neglected. The aims of the present research are to evaluate (1) how comfort perception varies as a function of the levels of acoustic noise, related to different comfort classes, by measuring comfort at the physiological and psychological level; and (2) whether the psychological state of participants can influence the physiological sensitivity to acoustic noise, thus modifying the noise levels which cause variations in the comfort experience.

1.1. The influence of noise level on physiological and psychological processes

Several studies in literature have shown that acoustic noise has negative effects on physiological and psychological health. Beside hearing troubles, the exposure to noise stress results in elevated blood pressure, cardiovascular diseases, sleep disturbances, subjective sensations of exhaustion, annoyance, reduction in social contacts, anxiety and depressive symptoms (Chang et al. 2009; Idrobo-Ávila et al. 2018; Nassur et al. 2019; Passchier-Vermeer and Passchier 2000; Seidler et al. 2017). At physiological level, noise acts as a stressor, causing alterations of the Autonomous Nervous System (ANS) activity (for a review see Idrobo-Ávila et al. 2018). Changes in the physiological response to noise have been found for different exposure durations (seconds, e.g. Park and Lee 2017; minutes, e.g. Lee, Chen, and Wang 2010; hours, e.g. Kraus et al. 2013), source types (white noise, e.g. Björ et al. 2007; floor impact noise, e.g. Park and Lee 2017; aircraft, rail-and road vehicles noise, e.g. Chang et al. 2009; Nassur et al. 2019; Sim et al. 2015), levels and frequency of noise (e.g. Lee, Chen, and Wang 2010; Walker et al. 2016).

The noise level, in particular, has been found to increase the physiological stress response. Lee, Chen, and Wang (2010) have shown that the exposure to white noise (for 5 min) between 50 and 80 dB(A) determines an increase of sympathetic ANS activity, as measured by the ratio of Low frequency (LF) to High frequency (HF) power. Park and Lee (2017) have shown that the exposure to floor impact noise [from 31.5 from 63 dB(A)] for less than 30 s increases the electrodermal activity and the respiration rate compared to a free-noise condition. Greater alterations in ANS activity by traffic air pollutants have been found at high noise level [greater or equal to 65 dB(A)] compared to low noise level [less than 65 dB(A)] (Huang et al. 2013). Heart rate alterations during sleep have been detected at 45–77 dB(A) for noise emitted from aircraft, rail-, and road vehicles (Griefahn et al. 2008). Sim et al. (2015) have shown that, for specific types of noise, the exposure to 45 dB(A) can also have a positive effect on health, causing an overall balance between the sympathetic and parasympathetic nervous system.

The effect of noise level is evident also at psychological level. Seidler et al. (2017) have found that road traffic noise between 40 dB(A) and 70 dB(A) can determine depressive symptoms. While, for other sources of noise (i.e. aircraft and railway noise), a reversed U-shape relationship has been found between depression and noise level, with a decrement of depression for higher noise levels [$>$50 dB(A)]. The level of noise also influences the degree of annoyance experienced by an individual during the noise exposure (Guski 1999; Park, Lee, and Jeong 2018; Passchier-Vermeer and Passchier 2000; Schreiber and Kahneman 2000; Versfeld and Vos 1997).

The negative effect of the noise level on physiological and psychological processes is thus sustained by several studies. However, to date, it is difficult to identify what are the levels of noise having more negative influence on individual health. This occurs especially because the studies differ for experimental design, noise qualities, duration of the exposure and physiological and psychological parameters which have been measured. There is not, indeed, clear evidence of how physiological and psychological processes are affected by short-term exposures to noise levels between 45 and 55 dB(A) [i.e. 45 dB(A), 47 dB(A), 50 dB(A), 55 dB(A)]. In the cruise sector, these intensities define different comfort classes of a ship cabin. The aim of the present study is to individuate whether a short-term exposure to these noise levels can determine different comfort experience in participants.

We measured comfort perception, implicitly, with physiological parameters (i.e. Heart Rate Variability, HRV), and, explicitly, by investigating the subjective perception of comfort and mood of participants.

1.2. The influence of emotional state on physiological comfort

Traditionally, comfort has been measured in terms of physiological reactivity during the exposure to an environmental stimulus (for a review see Cole et al. 2008). In particular, several studies investigated the variation of the ANS activity as response to different levels of an external stimulus. Normally, an increase of the ANS response is related to an increase of discomfort. Physiological comfort has been studied in relation to acoustic noise (e.g. Björ et al. 2007; Lee, Chen, and Wang 2010), vibration (e.g. Monazzam et al. 2018; Zhang et al. 2018), air temperature, (e.g. Liu, Lian, and Liu 2008; Wang and Liu 2020), and ambient light (e.g. Cajochen et al. 2005; Schäfer and Kratky 2006).

According to recent studies, physiological reactivity to a stressor and the subjective perception of comfort can be influenced by perceptual processes and emotional states. At instance, Wang and Liu (2020) have found that the response of the autonomous sympathetic and parasympathetic systems to thermal stimuli varies as a function of the emotional state of participants. During the exposure to a thermal stimulus, sympathetic activity and judgments of discomfort are higher for participants under boring states compared to participants in a joyful or neutral state. Instead, parasympathetic activity increases for participants in a joyful compared to neutral state. Hughes and Stoney (2000) have found that subjects in a high depressed mood (according to the Beck Depression Inventory) show a lower activity of parasympathetic system in response to cold stimuli when compared to subjects in a low depressed mood. Light exposure too causes different levels of parasympathetic activity, when comparing people in normal or dysphoric state (Choi et al. 2011).

Other studies have found that positive and negative emotions can influence the cardiovascular reactivity and the recovery from stress (Fredrickson and Levenson 1998; Fredrickson et al. 2000; Kaczmarek et al. 2019; Pressman, Jenkins, and Moskowitz 2019). Kaczmarek et al. (2019) have found that the exposure to positive stimuli before a stressful task determines, during the task, a lower diastolic blood pressure reactivity and, after the task, a stronger blood pressure recovery when compared to the exposure to neutral stimuli. This evidences the health protective effects of positive emotions (see also Pressman, Jenkins, and Moskowitz 2019). Radstaak, Geurts, Brosschot, Cillessen, and Kompier (2011) found a slower systolic blood pressure recovery from participants watching a movie with a negative emotional valence, than participants watching a movie with a neutral emotional valence. Hostility and aggression are significantly associated with increased cardiovascular reactivity; in contrast, anxiety, neuroticism, or negative affect are associated with decreased cardiovascular reactivity after stress (for a review see Chida and Hamer 2008).

The influence of psychological factors on physiological response has also been found during noise exposure. Park, Lee, and Jeong (2018) have shown that people more sensitive to noise exhibit greater changes in physiological activity during the exposure to floor impact noise between 40 and 60 dB(A), and greater annoyance ratings compared to people less sensitive to noise. The sensitivity to noise has been found to be positively correlated with introversion, depression, anxiety, insomnia and stress (Park et al. 2017; Standing, Lynn, and Moxness 1990). Introverts show higher physiological activation during the exposure to white noise at 60 dB(A) compared to extroverts (Standing, Lynn, and Moxness 1990). A greater increase of respiration rate in response to noise has also been found between people who have past experience of noise exposure compared to people with no past experience (Park and Lee 2017).

In summary, all these studies evidence that psychological factors can have a relevant role in determining psychophysiological responses to environmental stressors, included acoustic noise. These findings are particularly relevant for comfort studies because suggest that the manipulation of the environmental stimuli characteristics alone does not guarantee variations in the comfort experience, while it is relevant to monitor the emotional state of the individual. Furthermore, these studies show as it is crucial to measure the relationship between physiological and psychological responses to determine the real comfort perception of the individual.

2. General method

In the present study, we evaluated comfort perception during the exposure to five sound pressure levels of white noise inside a ship cabin. Four noise intensities correspond to the levels of noise defining different comfort thresholds for the Classification Societies [i.e. 45 dB(A), 47 dB(A), 50 dB(A), 55 dB(A)] and a 30 dB(A) condition which represents the baseline. During the exposure to each level of acoustic noise, autonomic response, subjective perception of comfort and mood were measured. The ANS response is measured in terms of short-term Heart Rate Variability (HRV). The ANS is mainly composed of the sympathetic nervous system and the parasympathetic nervous system. Continuous changes in sympathetic and parasympathetic activity exhibit alterations in the Heart Rate (HR) and cause oscillation of the R–R interval around its mean value (HRV). Time-domain and frequency-domain indices were used as measures of HRV (Malik et al. 1996).

We used the single item scale adapted from Ellermaier Pain Scale (Ellermeier, Westphal, and Heidenfelder 1991) for the assessment of subjective comfort, and the Profile of Mood State (POMS) questionnaire (Terry, Lane, and Fogarty 2003) for the assessment of mood.

2.1. Participants

Twenty-two subjects (17 women, *M*age = 22.67, age range: 19–33 years) participated voluntarily in the experiment. All participants were healthy; in a baseline interview they did not report auditory, neurological, and cardiopulmonary disorders that could prevent the subject from performing experimental procedure. Thus, we did not perform an audiometry test and otoscopy to detect any ear-related disorders (e.g. hearing impairment or annoyance by noise). They had normal or corrected-to-normal vision and were naïve to the purpose of the study. None of them had been previously exposed to the stimuli employed in the present experiment. Mostly, they were students of the University of Trieste and received class credit for participation. The study was approved by the Research Ethics Committee of the University of Trieste (approval number 80) and was conducted in compliance with national legislation, the Ethical Code of the Italian Association of Psychology, and the Code of Ethical Principles for Medical Research Involving Human Subjects of the World Medical Association (Declaration of Helsinki). All participants provided their written informed consent prior to the inclusion in the study.

2.2. Apparatus and stimuli

Figure 1 shows the plan view and a snapshot of the full-scale mock-up of the ship cabin which we used as experimental setting. Our mock-up is a reproduction of a real cabin, provided by Fincantieri's shipyard (Trieste, Italy), with the furniture, ambient lighting and sound system reproducing exactly those used inside the real cabin (the same mock-up has been used in the study of Nolich et al. 2019).

Acoustic white noise was generated on a high-performance PC soundcard, amplified trough a ZZip ZZMXBTE4 mixer and diffused into the cabin mock-up with two Genelec 8030 monitor loudspeakers, positioned at the same distance (i.e. 170 cm), to the right (Figure 1(B), above the cabinet) and left of participant (Figure 1(B), above the minibar), at a height of approximately 150 cm. It was possible to guarantee a range of variation for the equivalent continuous A-weighted sound pressure level equal to $35-75$ dB(A) of a sample of white noise featured from the interior of a cabin ship. The noise was characterised by no periodicity in time and an approximate constant amplitude over the frequency spectrum, with a 35 dB(A) intensity value referring to measurements sampled during a state of standstill of the ship. Laboratory settings allows for a mock-up cabin sound pressure level around 35 dB(A) ± 1 dB(A). Ambient light condition has been reproduced through a Philips HUE wireless lighting system. It includes four Dimmable LED bulbs of 10 W each, a dimmer switch and a base (bridge) that allows remote control (Philips Hue, v. 3.20.1, 7162). The lamps were installed in the cabin ceiling in the same positions they have in a real cruise cabin on board, providing an even light distribution within the cabin volume (Figure 1(B)). Lamps were positioned in order to no direct light arrives to the participants' eyes and that no light has been reflected from the mirror to the participant's eye. The balcony door was obscured with two curtains to admit no daylight. The nominal HSV, luminance and Colour Correlated Temperature values at which we settled our light condition were: S0 V100, 6.25 cd/m^2, CCT = 4996 K.

2.3. Psychological measures

After each acoustic noise exposure, participants rated orally their discomfort state on a 0–50 scale (adapted from the Ellermeier's Pain Scale, Ellermeier, Westphal, and Heidenfelder 1991), with 0 = *exposure felt completely natural*; 25 = *exposure felt slightly unnatural* as causing a moderate discomfort; 50 = *exposure felt completely unnatural* as causing a severe discomfort (Fantoni and Gerbino 2014). Individual ratings of discomfort (namely Estimated Discomfort) were successively expressed and analysed as relative scores taking

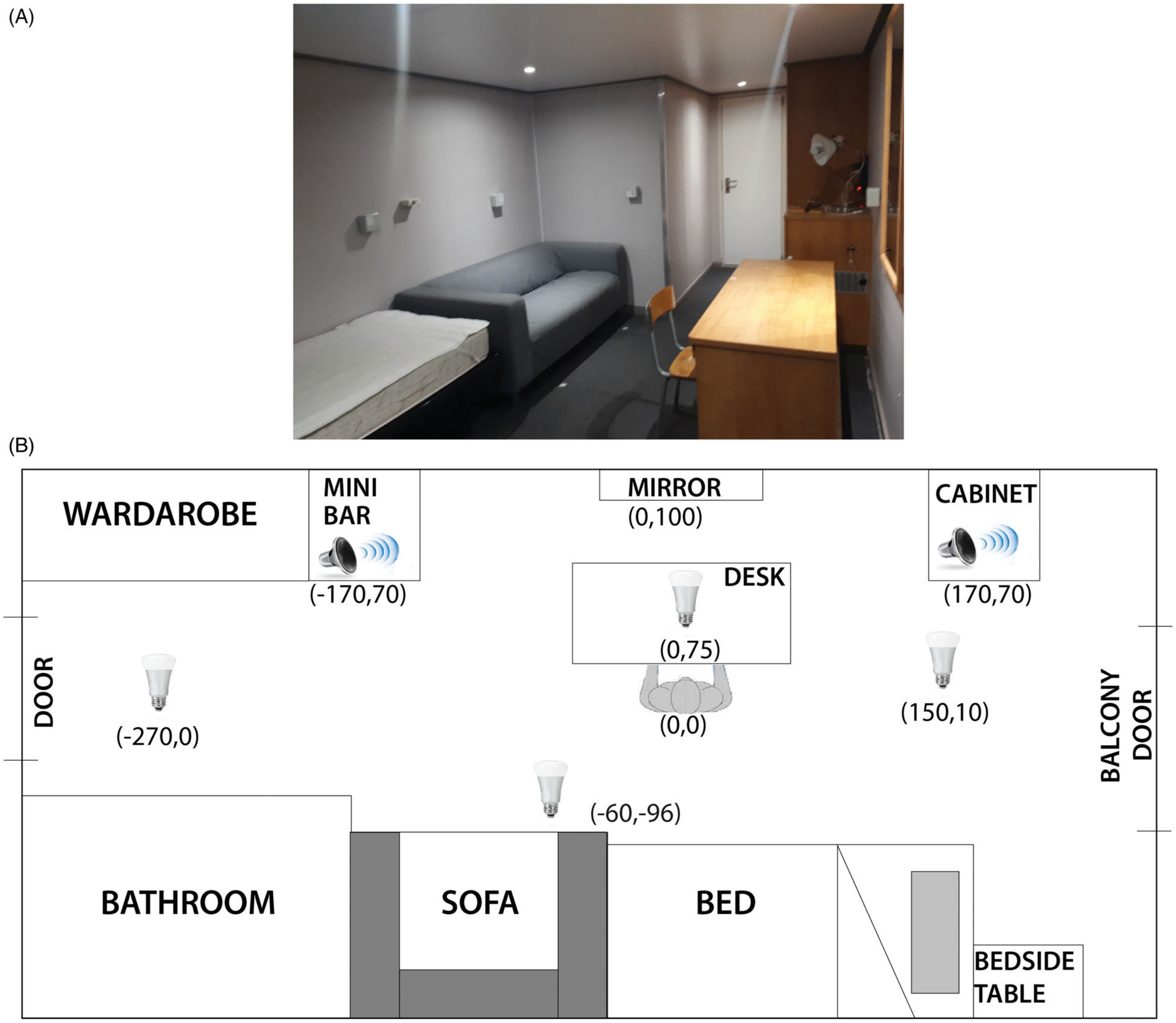

Figure 1. (A) A snapshot of the cabin setup provided by the Fincantieri S.p.A. under the ambient light condition of the experiment. (B) Plan view of the full-scale mock-up of the ship cabin used as Experimental setup. The cabin is divided into a sleeping area (including a single size bed and a bedside table), a living area (including a chair, a desk, a mirror above the desk, a cabinet, one minibar, and a small sofa), a bathroom (not accessible area), and an entrance with a small wardrobe and a balcony door. The cabin dimensions, including the bathroom, were 3 × 6 m × 2.20 m height. The position of the four lamps on the ceiling, the two loudspeakers and the mirror are expressed in (*x,y*) coordinates (cm) with the origin of the reference axis centred in point of view of the participant.

the ratio between the value indicated by the subject on the scale and the maximum value of the scale, with 1 standing for a score corresponding to the maximum of the Discomfort scale (*severe discomfort*) and 0 for a score corresponding to the minimum of the Discomfort scale (*completely natural*). As an explicit measure of the mood state, we utilised the POMS questionnaire (24-items version, Terry, Lane, and Fogarty 2003; Terry et al. 1999). Participants rated their level of agreement on a 1–5 Likert scale (0 = *Not At All*; 1 = *A Little*; 2 = *Moderately*; 3 = *Quite a lot*; 4 = *Extremely*) to indicate how well each adjective of a set of 24 (describing sensations that everybody can commonly feel) best described how they felt in that specific moment after the exposure to acoustic noise. The 24 adjectives of the POMS questionnaire can be categorised into six subcategories including Tension-Anxiety (TEN), Depression-Dejection (DEP), Anger-Hostility (ANG), Fatigue (FAT), Confusion (CON), and Vigour (VIG). A low score for TEN, DEP, ANG, FAT, and CON and a high score for VIG represent a more positive emotional condition. The Total Mood Disturbance (TMD) score was calculated

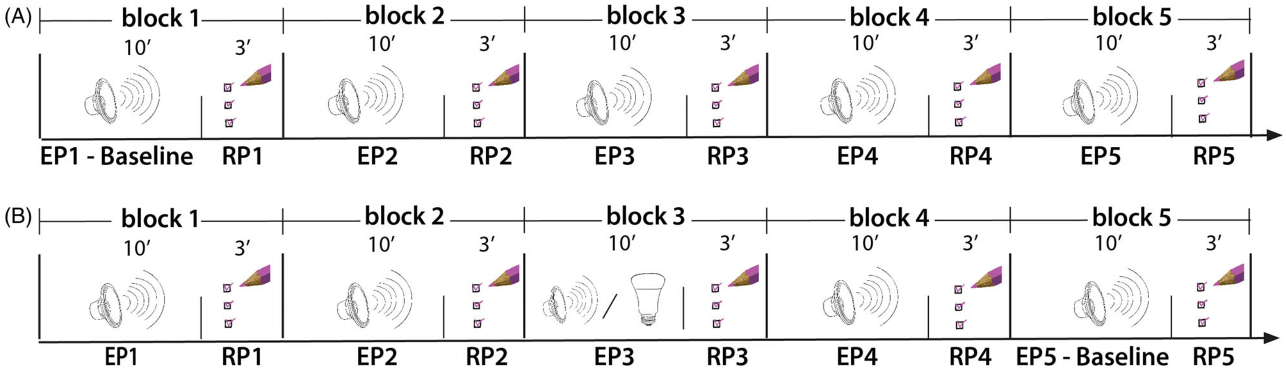

Figure 2. Temporal sequence of phases in the experiment. (A and B) depict the five blocks of the experiment each including two successive phases: Exposure Phase (EP – lasting 10′, from EP1 to EP5) and the successive Rating Phase (RP – lasting 3′, from RP1 to RP5). During each EP, participants were randomly exposed to one of five different noise intensities, with the order of presentation of the Baseline intensity counterbalanced across observers. During RP, participants filled the POMS questionnaire and responded orally to the Discomfort scale. Half of the participants performed the sequence of blocks in A (Baseline at the Beginning with EP1 – RP1) and half the sequence of blocks in B (Baseline at the End with EP5 – RP5).

according to the Grove and Prapavessis (1992) formula in order to avoid negative scores:

$$\text{TMD} = 100 + [\text{TEN} + \text{DEP} + \text{ANG} + \text{FAT} + \text{CON}] - [\text{VIG}] \quad (1)$$

2.4. Physiological measures

The duration of RR-intervals was measured during time periods of 5 min, and on spectral analysis basis HRV was determined. The software accompanying the device permitted an export of HRV data into text files that could be analysed by a computer programme which determined time-domain and frequency-domain variables. For the time-domain, we evaluated the following: standard deviation of normal to normal intervals (SDNN) (an estimate of overall HRV), square root of the mean normal to normal interval (RMSSD) (an estimate of short-term components of HRV and a measure of parasympathetic activity), and percentage of adjacent pairs of normal to normal intervals differing by more than 50 ms in the recording (pNN50) (higher values indicate increased relaxation). In the frequency-domain, the spectra of high frequency (HF: 0.15–0.40 Hz, normalised units) and low frequency (LF: 0.04–0.15 Hz, normalised units) as well as their ratio (LF/HF ratio, an index of sympathovagal influence on the heart) were analysed according to the recommendations by the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (Malik et al. 1996). The efferent vagal activity is a major contributor to the HF component, an increase in the LF is considered a marker of increasing autonomic influence (sympathetic and parasympathetic), and an increase in the LF to HF ratio accounts for rising sympathetic influence. The 5-min averages of HR and time-domain HRV parameters were determined for every 5-min interval with at least 200 beats recorded, and 5-min averages of frequency-domain parameters were determined for intervals with at least 300 beats recorded.

2.5. Procedure

All participants were required not to smoke or drink alcoholic or caffeinated beverages for 24 h before the evaluation. Before the beginning of the experiment, they underwent a brief medical anamnesis (i.e. medical diseases or treatments, smoking habits, physical activity) and their heartbeat and blood pressure were measured. They were then equipped with the digital Holter recorder (Cardioline Clickholter), sat on a chair in front of a desk facing the mirror placed at a distance of 100 cm. The subjects were connected to the digital holter recorder by five electrodes attached to the chest for recording electrocardiogram signals and subsequent calculation of HRV parameters (see Supplementary Figure S1 of the supplementary material for the exact positions of the electrodes).

As instruction, they were asked to fixate the tip of their nose reflected on the mirror just in front of them during the acoustic noise exposure. We selected such fixation point to provide a constant spatial reference for all participants in terms of familiarity and position with respect to the optical axis. Furthermore, self-face represents an equally experienced stimulus for all participants as necessary to produce maximally similar level of ANS activity beyond experimental manipulations (e.g. Kreibig 2010).

In particular, each experimental session included five successive blocks, each constituted by two successive phases (Figure 2(A,B)):

1. An exposure phase EP (lasting 10′), during which the cardiac rhythm was recorded (i.e. two consecutive 5-min digital Holter recordings), while participants were exposed to the different intensities of acoustic noise.
2. A rating phase RP (lasting 3′), with no noise exposure, during which participants filled the POMS questionnaire and responded to the single item of the Discomfort scale orally. On average, the RP, lasted less than the whole allotted 3′ time, allowing a rest period, without any task to perform, of about 1.5 min.

To control the ordering of the sequence, the order of presentation of the noise intensity Baseline condition was counterbalanced across observers with half of the observers starting (Figure 2(A)) and half finishing (Figure 2(B)) the exposure sequence with the Baseline. The other levels of noise intensities were presented in random order. During all the experiment, an experimenter was inside the cabin to record the participant's responses and to control that he/she maintained the correct position, while a second experimenter was outside the cabin in order to administer and regulate the intensity levels of acoustic noise. Two cameras were positioned inside the cabin in order to allow the second experimenter to monitor participant's performance online and to decide when to start a new experimental block.

2.6. Data analysis

We used R (R Core Team, 2018) and lme4 (Bates et al. 2015) to perform two types of linear mixed effects (*lme*) analyses. *Analysis 1* was aimed at evaluating the effect of acoustic noise intensities on single physiological and psychological measures of comfort (HRV frequency-domain and time-domain indices, Estimate Discomfort, TMD, and POMS factors); *Analysis 2 a–b* was focussed at evaluating whether the subjective perception of comfort (*Analysis 2a*) and mood state (*Analysis 2 b*) have a moderation effect on physiological response during the exposure to each acoustic noise levels.

For *Analysis 1,* we used *lme* models, with participant and the order of the LF/HF ratio registrations as random intercepts (see paragraph S2 of the supplementary material for the preliminary analyses) and Acoustic Noise as fixed effect. The fixed structure of the *lme*s was selected according to a stepwise procedure, contrasting *lme*s of increasing complexity, depending on the number of fixed effects (Bates 2010; Bates et al. 2015). We added to the *lme*-models, for *Analysis 2a,* the Estimated Discomfort and, for *Analysis 2 b*, the other indices of mood (i.e. TMD and the POMS factors) as continuous covariates of HRV.

We followed Bates (2010) and used the same statistical procedure to obtain two-tailed *p*-values, by means of likelihood ratio test based on χ^2 statistics, when contrasting *lme*s with different complexities (for a discussion of advantages of a *lme* procedure over the more traditional mixed models analysis of variance see Kliegl et al. 2010). AIC-index was used as a supporting comparative measure of the goodness of fit. Furthermore, we used type 3-like two tailed *p*-values for significance estimates of *lme*'s fixed effects and parameters adjusting for the *F*-tests the denominator degrees-of freedom with the Satterthwaite's (1946) approximation based on SAS proc mixed theory. Among the indices that have been proposed, as reliable measures of the predictive power and of the goodness of fit for *lme* models, we selected the concordance correlation coefficient r_c, which provides a measure of the degree of agreement between observed and predicted values in the [−1, 1] range (Rigutti, Fantoni, and Gerbino 2015; Vonesh, Chinchilli, and Pu 1996) and the coefficient of determination r^2. Post-hoc tests were performed on *lme* estimated coefficients with paired two sample t-tests with unequal variance.

We determined the required sample size using G*Power (Faul et al. 2007). We performed two a-priori power analysis which have shown similar results. One analysis was based on a repeated measures ANOVA, with a within subject design and acoustic noise as independent variable, with 5 different levels (i.e. acoustic noise: 30 dB(A), 45 dB(A), 47 dB(A), 50 dB(A) and 55 dB(A)) and two groups of participants (i.e. participants starting the exposure sequence with the Baseline condition [30 dB(A)] and participants finishing the exposure sequence with the Baseline condition). Assuming a power of .9, $\alpha = .05$, an effect size of .25 and a correlation among the repeated measures of .7, the analysis revealed a sample size of 17 participants, with $F = 2.51$. The other power analysis was based on χ^2 statistics used to perform the linear mixed effects analyses of the relationship between acoustic noise and physiological and psychological measures of comfort. Assuming a power of .9, $\alpha = .05$, an average

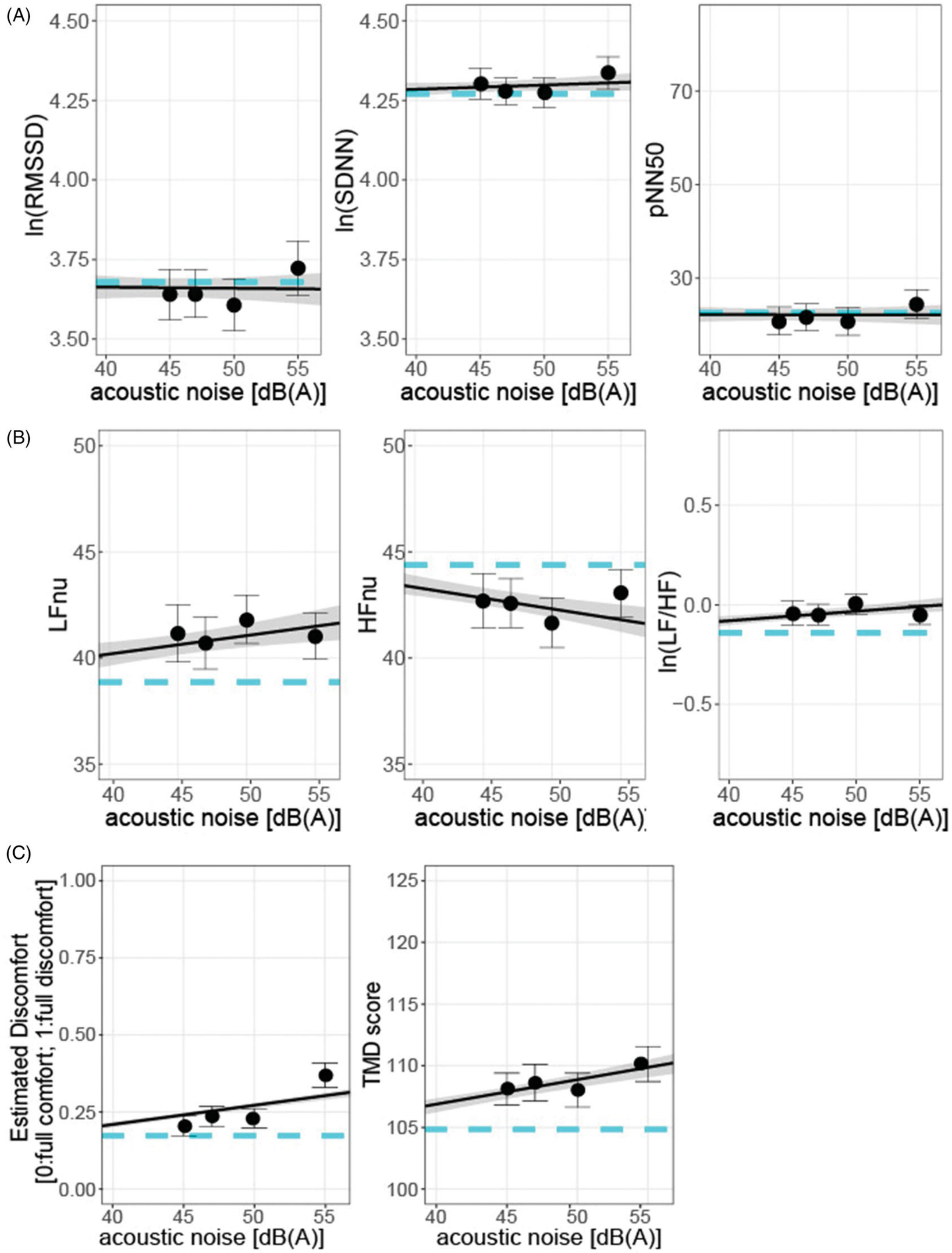

Figure 3. (A–C) The average of time-domain (A), frequency-domain (B) indices of HRV and the main psychological measures (C) as a function of the four acoustic noise intensities relative to the Grand Average value for the 30 dB(A)-Baseline condition (cyan dotted line). Error bars represent ± 1 standard error of the mean. Black continuous lines are best fitting *lme* model regression lines, with the shaded region corresponding to ± 1 standard error of the regression.

effect size of .3 and 5 degrees of freedom (corresponding to the 5 levels of the independent variables [acoustic noise]), the analysis revealed a sample size of 183 observations. As, at the best, we have two measurements of the dependent variable for each level of acoustic noise (two short-term recordings of HRV of 5 min), the sample size should be 183 observations/(5 levels * 2 recordings) ≃18 subjects. We used the *powerSim* function of the *simr* R package (Green and MacLeod 2016) to perform the post-hoc power

Table 1. *lme*-estimates of the effect of Acoustic Noise on HRV time-domain and frequency-domain indices and on psychological measures.

	All participants ($N = 22$)			
	Slope (mean ± SE)	*t*	*df*	*p*
RMSSD	0 ± .001	−.24	164	.8070
SDNN	.001 ± .001	1.33	164	.1850
pNN50	−.005 ± .056	−.09	164	.9260
LF	.087 ± .033	2.67	165	.0084**
HF	−.102 ± .029	−3.25	165	.0007**
LF/HF ratio	.005 ± .001	3.93	165	.0009**
Estimated Discomfort	.006 ± .001	5.79	165	<.0001**
TMD	.199 ± .046	4.33	165	<.0001**

RMSSD: square root of the mean normal to normal interval; SDNN: standard deviation of normal to normal intervals; pNN50: percentage of adjacent pairs of normal to normal intervals differing more than 50 ms; LF: low frequency; HF: high frequency; LF/HF ratio: low frequency to high frequency ratio; Estimated Discomfort: the ratio between the value indicated by the subject on the Discomfort scale and the maximum value of the scale; TMD, total of mood disturbance score.
Significance codes: $^{**}p < .01$.

analysis to detect the significance of the fixed effects in our *lme* models. The estimated power of *Analysis 1* [fixed effect: Acoustic Noise] and *Analysis 2* [fixed effect: Acoustic Noise × Estimated Discomfort] *lme* models are about 93% and 76%, respectively.

3. Results

3.1. The influence of acoustic noise on physiological and psychological measures

As we can see in the Figure 3(A), the analysis of time-domain HRV indices evidenced that acoustic noise intensities did not influence RMSSD, $\chi^2_1 = .06$, $p = .8063$, SDNN, $\chi^2_1 = 1.77$, $p = .1831$ and pNN50, $\chi^2_1 = .01$, $p = .9256$. In fact, their values are approximately the same for all noise intensities (see Table 1 for all the *lme*-estimates).

Figure 3(B), instead, shows a significant effect of acoustic noise on HRV frequency-domain indices. The LF/HF ratio and LF increase as a function of acoustic noise, instead HF decreases (Table 1). These results are confirmed by the *lme* analysis which showed a main effect of Acoustic Noise on the LF/HF ratio, $\chi^2_1 = 11.19$, $p = .0008$, LF, $\chi^2_1 = 7.02$, $p = .0081$, and HF, $\chi^2_1 = 11.63$, $p = .0006$ (see Table 2 for the goodness of fit indices of *lme*-models for *Analysis 1*).

The post-hoc analysis revealed significant differences between the LF/HF ratio, LF and HF observed by the exposure at 30 dB(A)-Baseline and the other noise intensities (Table 3).

Regarding the effect of acoustic noise on psychological measures, we found that the average Estimated Discomfort and TMD scores increased as the acoustic noise intensities become higher (Figure 3(C)).

Table 2. Goodness of fit indices of *lme*-models for *Analysis 1* and *Analysis 2a–b*.

	df	r^2	r_c	*IC*	*AIC*
LF/HF ratio					
∼ 1	3	.82	.89	[.86, .92]	−19
∼ Acoustic Noise	4	.83	.90	[.87, .92]	−28
∼ *Acoustic Noise × Estimated Discomfort*	6	.83	.90	[.88, .93]	−31
∼ *Acoustic Noise × TEN factor*	6	.84	.90	[.88, .93]	−33
LF					
∼ 1	3	.81	.89	[.86, .91]	1288
∼ Acoustic Noise	4	.82	.89	[.86, .91]	1283.4
∼ *Acoustic Noise × Estimated Discomfort*	6	.82	.90	[.87, .92]	1279
∼ *Acoustic Noise × TEN factor*	6	.83	.90	[.87, .92]	1278.9
HF					
∼ 1	3	.84	.91	[.88, .93]	1260
∼ Acoustic Noise	4	.85	.91	[.89, .93]	1250.5
∼ *Acoustic Noise × Estimated Discomfort*	6	.85	.91	[.89, .93]	1249.9
∼ *Acoustic Noise × TEN factor*	6	.85	.92	[.89, .93]	1248.2
Estimated Discomfort					
∼ 1	3	.68	.78	[.73, .82]	−138
∼ Acoustic Noise	4	.73	.83	[.78, .86]	−166
TMD					
∼ 1	3	.69	.80	[.75, .84]	1419
∼ Acoustic Noise	4	.73	.82	[.78, .86]	1403

Experiment-specific linear mixed-effects models exploring the effects of Acoustic Noise (four intensities and 30 dB(A)-baseline) or their absence (intercept-only null model) on frequency-domain HRV indices (LF/HF ratio, LF and HF) and psychological measures (Estimated Discomfort and TMD scores). Mixed-effect models for *Analysis 2a-b* including as fixed effect the interaction term between Acoustic Noise and Estimated Discomfort (*Analysis 2a*) and between Acoustic Noise and TEN factor (*Analysis 2b*) are italicised. LF/HF ratio, low frequency to high frequency ratio; LF, low frequency; HF, high frequency; Estimated Discomfort, the ratio between the value indicated by the subject on the Discomfort scale and the maximum value of the scale; TMD: total of mood disturbance score; *df*: degrees of freedom of the model; r^2: coefficient of determination: r_c: concordance correlation coefficient; *IC*: the confidence interval at 95% of r_c; *AIC*: the Akaike Information Criterion index.

The *lme* analyses validated these observations revealing a main effect of Acoustic Noise on Estimated Discomfort, $\chi^2_1 = 30.66$, $p < .001$, and TMD, $\chi^2_1 = 17.81$, $p < .001$ (see paragraph S4 of the supplementary material for the effect of noise on POMS factors). In general, post-hoc analysis revealed significant differences in TMD, between 30 dB(A)-Baseline and the other noise intensities, as well as in Estimated Discomfort, between 55 dB(A) and the other levels of noise (Table 3).

3.2. The influence of psychological state on physiological response to acoustic noise

Our further *lme* analyses, controlling for the effect of psychological measures on physiological response, are limited to frequency-domain indices, because, as we have seen previously, no effect of acoustic noise on time-domain indices has been found. These analyses revealed that the effect of acoustic noise on autonomic response is moderated by the subjective perception of comfort (measured by the Estimated Discomfort) and anxiety (measured by the TEN factor of POMS questionnaire).

Table 3. Post-hoc comparisons between all acoustic noise intensities for HRV frequency-domain indices and psychological measures.

	LF/HF ratio		LF		HF		Estimated Discomfort		TMD	
dB(A)	χ^2_1	p	χ^2_1	p	χ^2_1	p	χ^2_1	p	χ^2_1	p
30−45	6.03	.0141*	4.34	.0371*	6.90	.0086**	.63	.4276	6.97	.0083**
30−47	4.49	.0341*	2.11	.1462	6.87	.0088**	3.40	.0653·	8.72	.0031**
30−50	13.47	.0002**	8.63	.0033**	14.31	.0001**	3.42	.0644·	6.44	.0111*
30−55	7.56	.0060**	4.74	.0294*	7.50	.0062**	55.63	.0000**	19.57	.0000**
45−47	.11	.7370	.41	.5218	.00	.9957	1.17	.2792	.11	.7392
45−50	1.57	.2097	.77	.3786	1.42	.2327	1.19	.2759	.01	.9157
45−55	.10	.7474	.01	.9112	.02	.8929	47.34	.0000**	3.45	.0631·
47−50	2.50	.1140	2.29	.1300	1.39	.2384	.00	.9993	.19	.6615
47−55	.43	.5138	.56	.4554	.02	.8979	33.10	.0000**	2.29	.1301
50−55	.85	.3560	.58	.4457	1.10	.2937	33.62	.0000**	3.85	.0496*

LF/HF ratio: low frequency to high frequency ratio; LF: low frequency; HF: high frequency; Estimated Discomfort: the ratio between the value indicated by the subject on the Discomfort scale and the maximum value of the scale; TMD: total of mood disturbance score.
Significance codes: *$p < .05$; **$p < .01$.

The results of the *lme* analysis show a significant interaction between the Estimated Discomfort and Acoustic Noise for the LF/HF ratio, $\chi^2_2 = 7.01$, $p = .0300$ and LF, $\chi^2_2 = 8.33$, $p = .0155$, but not for HF, $\chi^2_2 = 4.57$, $p = .1019$ (see Table 2 for the goodness of fit indices of *lme*-models of *Analysis 2a*). In particular, the relationship between the LF/HF ratio, LF and Acoustic Noise changes from positive to negative, and the relationship between HF and Acoustic Noise changes from negative to positive, as the Estimated Discomfort changed from *Low* to *High* (LF/HF ratio: $\beta = -.020 \pm .008$, $t_{168} = -2.50$, $p = .0132$; LF: $\beta = -.484 \pm .188$, $t_{168} = -2.57$, $p = .0110$; HF: $\beta = .366 \pm .172$, $t_{166} = -2.50$, $p = .0347$).

A significant interaction has also been found between the TEN factor scores and Acoustic Noise for the LF/HF ratio, $\chi^2_2 = 8.45$, $p = .0146$, LF, $\chi^2_2 = 8.53$, $p = .0145$, and HF, $\chi^2_2 = 6.23$, $p = .0444$ (see Table 2 for the goodness of fit indices of *lme*-models of *Analysis 2 b*). The relationship between the LF/HF ratio, LF and and Acoustic Noise changes from positive to negative, and the relationship between HF and Acoustic Noise changes from negative to positive, as the TEN factor changes from *Low* to *High* (LF/HF ratio: $\beta = -.003 \pm .001$, $t_{164} = -2.89$, $p = .0044$; LF: $\beta = -.073 \pm .025$, $t_{164} = -2.57$, $p = .0039$; HF: $\beta = .056 \pm .023$, $t_{164} = 2.44$, $p = .0157$).

In order to better qualify the 2-way interaction between Estimated Discomfort/TEN factor scores and Acoustic Noise, we further conducted four separated *lme*-analyses, one for each group of participants obtained performing the median split of the Estimated Discomfort ratings (*Low* discomfort group: $N = 11$, 10 women, $M_{age} = 22.54$, age range: 19–33 years; *High* discomfort group: $N = 11$, 7 women, $M_{age} = 22.80$, age range: 19–30 years) and the median split of the TEN factor ratings (*Low* anxiety group: $N = 11$, 9 women, $M_{age} = 22.91$, age range: 19–33 years; *High* anxiety group: $N = 11$, 8 women, $M_{age} = 22.40$, age range: 19–30 years).

As we can see in the Figure 4, the relationship between the LF/HF ratio, LF, HF and Acoustic Noise was significant in the *Low* discomfort group (LF/HF ratio: $\chi^2_1 = 8.58$, $p = .0034$; LF: $\chi^2_1 = 5.49$, $p = .0191$; HF: $\chi^2_1 = 9.58$, $p = .0020$), but not in the *High* discomfort group (LF/HF ratio: $\chi^2_1 = 3.25$, $p = .0713$, LF: $\chi^2_1 = 2.26$, $p = .1326$; HF: $\chi^2_1 = 2.58$, $p = .1079$). In the *Low* discomfort group, there was an increase of the LF/HF ratio, LF and a decrease of HF as a function of Acoustic Noise (see Table 4 for all the *lme*-estimates).

The same occurs for the TEN factors scores (Figure 5). The relationship between frequency-domain indices and Acoustic Noise was significant in the *Low* anxiety group (LF/HF ratio: $\chi^2_3 = 19.02$, $p = .0003$; LF: $\chi^2_3 = 15.52$, $p = .0014$; HF: $\chi^2_3 = 18.19$, $p = .0004$), but not in the *High* anxiety group (LF/HF ratio: $\chi^2_1 = .49$, $p = .4839$, LF: $\chi^2_2 = 3.52$, $p = .1716$; HF: $\chi^2_1 = .73$, $p = .3913$). For the *Low* anxiety group, there was an increase of the LF/HF ratio, LF and a decrease of HF as a function of Acoustic noise (see Table 4 for all the *lme*-estimates).

No other reliable interactions were found between other psychological indices of mood state and acoustic noise intensities.

4. Discussion

4.1. The effect of noise level on physiological and psychological processes

We found that physiological and psychological discomfort measures increase with the increment of acoustic noise level. This is indicated by the decrease of HF (i.e. parasympathetic activity), and the increase of LF, the LF/HF ratio (i.e. sympathetic activity), Estimated Discomfort, and TMD.

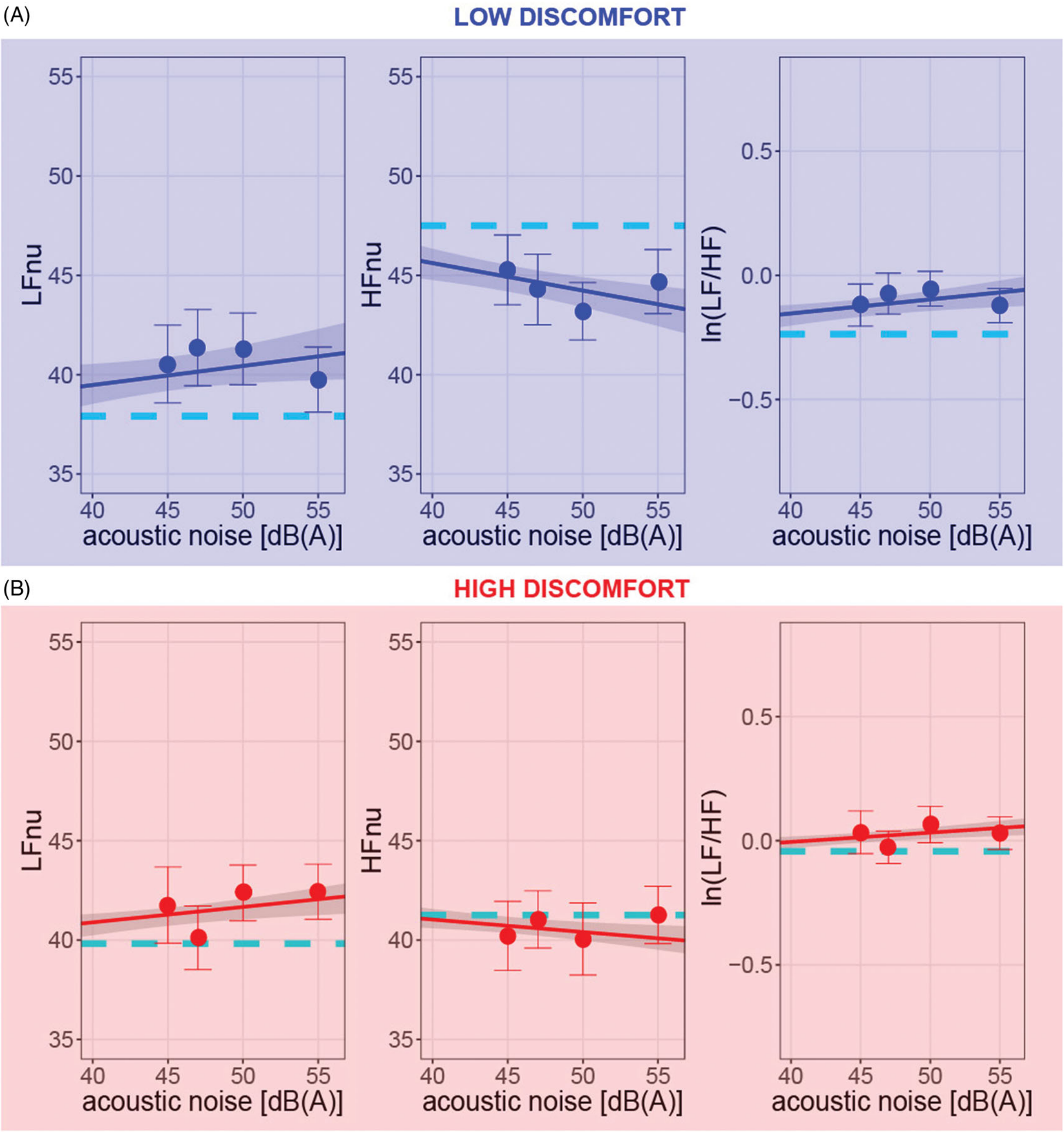

Figure 4. (A–B) The average of frequency-domain indices of HRV for the two groups of participants obtained performing the median split of their average discomfort rating, with the *Low* discomfort group in (A) and the *High* discomfort group in (B). Panels' colour encodes for the overall level of Estimated Discomfort according to the participant rating, with light-blue panel (A) encoding a positive state according to average discomfort ratings vs. light red panel (B) encoding a negative state according to average discomfort ratings. In A and B, the cyan dotted line corresponds to the Grand average for the 30 dB(A)-Baseline in each group. Error bars represent ±1 standard error of the mean. Blue and Red continuous lines are best fitting *lme* model regression lines for globally positive and negative Estimated discomfort state respectively, with the shaded region corresponding to ±1 standard error of the regression.

Our results confirm previous findings which have shown that noise level affects the activity of sympathetic and parasympathetic systems. Lee, Chen, and Wang (2010) found an increase in sympathetic activity (i.e. LF and LF/HF ratio) for short-term exposures to white noise at intensity level between 50 and 80 dB(A). Kraus et al. (2013), instead, evidenced a different involvement of the two ANS systems according to the level of noise exposure. The authors have shown a decrease in LF and HF for noise intensities below 65 dB(A) and an increase in the two powers for intensities above 65 dB(A). They also found an increase in LF/HF ratio for noise exposure above and below 65 dB(A), with a greater effect for intensities below 65 dB(A). The authors suggested that increases in higher noise intensities, which are more stressful, lead to a reduction in HRV due to an increase of sympathetic activation and additional release of stress hormones. While, increments in lower noise intensities might be attributable to parasympathetic withdrawal. This hypothesis is confirmed by other studies. The decrease in parasympathetic tone has been found at

Table 4. *lme*-estimates of the effect of acoustic noise on HRV frequency-domain indices for the four groups of participants obtained performing the median split of the Estimated Discomfort ratings and TEN factor scores.

	Slope (mean ± SE)	*t*	*df*	*p*
Low discomfort group ($N = 11$; Median discomfort ratings <= .22)				
LF	.096 ± .041	2.37	82	.0203*
HF	−.138 ± .044	−3.17	82	.0022**
LF/HF ratio	.011 ± .003	3.60	81	.0005**
High discomfort group ($N = 11$; Median discomfort ratings > .22)				
LF	.077 ± .051	1.50	82	.1370
HF	−.063 ± .039	−1.61	81	.1100
LF/HF ratio	.004 ± .002	1.81	81	.0736
Low anxiety group ($N = 11$; Median TEN factor scores <= .45)				
LF	.156 ± .043	3.64	81	.0005**
HF	−.167 ± .044	−3.81	81	.0002**
LF/HF ratio	.008 ± .002	4.04	81	.0001**
High anxiety group ($N = 11$; Median TEN factor scores > .45)				
LF	.013 ± .048	.27	83	.7880
HF	−.032 ± .038	−.86	82	.3940
LF/HF ratio	.001 ± .002	.70	82	.4870

LF: low frequency; HF: high frequency; LF/HF ratio: low frequency to high frequency ratio.
Significance codes: *$p < .05$; **$p < .01$.

intensities lower than 30 dB(A) (Graham et al. 2009), and not at intensities between 50 and 80 dB(A) (Lee, Chen, and Wang 2010) or at 85 dB(A) (Björ et al. 2007). Our finding of a parasympathetic withdrawal is in accordance with the study of Kraus et al. (2013). Indeed, we exposed participants to low noise intensities [between 30 and 55 dB(A)]. However, we also evidenced an increase in sympathetic activity. The physiological response to noise levels has been found to vary according to the source type (e.g. Sim et al. 2015), the duration of the exposure (Park et al. 2017) and the frequency of noise (e.g. Walker et al. 2016). These differences in laboratory setting may explain the disagreement between our findings and other studies. Kraus et al. (2013) exposed participants to individual daytime noise exposure, while we exposed participants to five specific noise intensities, in a laboratory setting and for short-term exposures. Park and Lee (2017) found an effect of noise level on electrodermal activity and respiration rate, but not on HR. The authors exposed participants at intensities of 31.5–63.0 dB(A), but they used a very short-term exposure (i.e. 23 s) and a different source of noise (i.e. floor impact noise). No noise level effect has also been found in a recent study, with a noise exposure to 5 min (Park, Lee, and Jeong 2018), for floor impact noise and road traffic noise. Also in this case, the sources of noise were different, and the authors exposed participants to only three different sound pressure levels [i.e. 40, 50 and 60 dB(A)].

We may hypothesise that also our specific setting (i.e. the ship cabin) may have influenced the physiological response to noise. There is evidence that the comfort experience related to noise, in a ship cabin, is different compared to other environments (Goujard, Sakout, and Valeau 2005; Kwortnik, 2008). Indeed, the noise effect can be influenced by the presence of other environmental stimuli inside the cabin, as the light and the temperature (Liu et al. 2018). Passengers reported to be particularly annoyed from all noises (e.g. other passengers, music) because they interfere with the tranquillity of the experience and the sounds of the sea (Kwortnik, 2008). In our study, almost all participants reported that they had been on a cruise. Our experimental setting, thus, may have elicited the specific sensations/reactions related to this experience, thus conditioning the physiological response to noise.

Our results also confirm the negative influence of noise level on individual psychological state. Previous studies have shown a negative effect of noise levels on noise annoyance ratings (Park, Lee, and Jeong 2018) and depressive and anxiety symptoms (Seidler et al. 2017). We found that also the temporary mood and the subjective perception of comfort can be negatively affected by noise. In particular, we evidenced a stronger effect of noise levels on temporary symptoms of anger, confusion, fatigue and vigour. Fatigue and vigour are psychological states related to physical sensations or feelings of boredom. While confusion is associated to a state of low cognitive efficiency, and anger to a feeling of frustration and irritation. The noise effect on anger may be related to the impossibility to get out from the cabin when the noise level exposure becomes too annoying.

4.2. The acoustic comfort classes according to physiological and psychological measurements

A more controversial aspect related to our study concerns the finding that physiological and psychological comfort's indices do not show the same pattern of variations in correspondence to the same levels of acoustic noise. Regarding the physiological response, we evidence a difference in LF, HF and the LF/HF ratio only between 30 dB(A) and the other noise exposure levels. This shows that the intensities of acoustic noise individuated by the comfort classes do not produce variations in physiological comfort. Psychological measures, instead, individuated a comfort threshold between 50 dB(A) and 55 dB(A). De facto, significant differences in discomfort judgments have been found between 55 dB(A) and the other noise intensities.

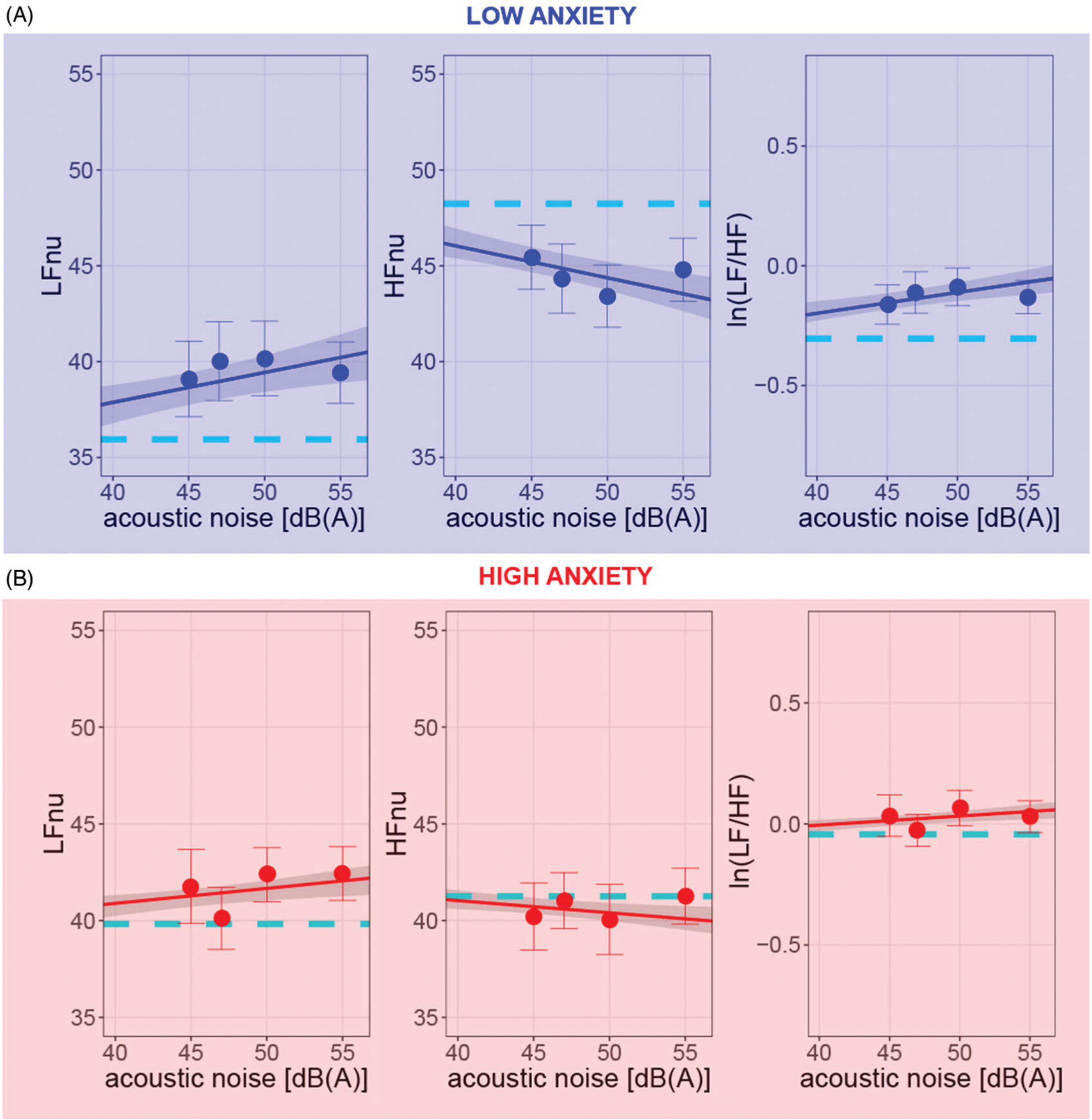

Figure 5. The average of frequency-domain indices of HRV for the two groups of participants obtained performing the median split of the TEN factors scores, with the *Low* anxiety group in (A) and the *High* anxiety group in (B). Panels' colour encodes for the overall level of TEN factor scores according to the participant rating, with light-blue panel (A) encoding a positive state according to TEN ratings vs. light red panel (B) encoding a negative state according to TEN ratings. In A and B, the cyan dotted line corresponds to the Grand average for the 30 dB(A)-Baseline in each group. Error bars represent ±1 standard error of the mean. Blue and Red continuous lines are best fitting *lme* model regression lines for globally positive and negative Estimated discomfort state respectively, with the shaded region corresponding to ±1 standard error of the regression.

These results individuate two different aspects. Firstly, if we consider the human component in defining comfort, the comfort thresholds individuated by the Classification Societies are too narrow and small variations of the intensity of acoustic noise [between 45 and 50 dB(A)] are not sufficient to produce a variation in the participants comfort perception (both at physiological and psychological level). Secondarily, physiological and psychological indices are not always in accordance in defining the comfort experience. In a study by Park, Lee, and Jeong (2018), annoyance ratings have been found to increase with the noise levels, instead this did not occur for physiological parameters.

This is a problem that can be traced back to a more general issue about how physiological and psychological processes interact (Damasio and Carvalho, 2013; LeDoux 2012; Mendes and Park 2014). According to recent studies, the evidence that a psychological state co-occurs with a certain physiological response does not mean that a physiological change always corresponds to a modification of the mental state (Mendes and Park 2014). The relationship between psychological and physiological response is not immediate, but there are several moderators between these two systems, such as context, cognitive and emotional processes. The concept of comfort is strictly related to the human physiology, but also to the human perception. For this reason, the research in comfort domain is very complex and many other studies are necessary to individuate methods which allow a consistent measurement of the human's global experience of comfort.

4.3. The effect of psychological state on physiological response to noise

The most important result of the present study concerns the influence of psychological state on physiological response to acoustic noise. As other authors have found for thermal and visual stimuli (Choi et al. 2011; Wang and Liu 2020), also during the noise exposure, the psychological state of participants modified comfort perception at the physiological level. In particular, we found that when participants have a higher subjective perception of discomfort and/or are in a state of higher anxiety, they show less variability in the physiological response to increments of acoustic noise intensities compared to when they have a lower subjective perception of discomfort and/or are in a state of lower anxiety. In other words, the subjective perception of the participants regarding their well-being state changed the effect of acoustic noise levels on physiological activation.

These results confirm previous evidence of an effect of the individual differences on the physiological response to noise. Some stable traits of personality have been found to influence how our physiological system responds to noise, as for example the sensitivity to noise (i.e. people which are more likely to pay attention to noise, to interpret noise negatively as a threat or annoyance and to react emotionally) and the introversion/extroversion (Park, Lee, and Jeong 2018; Standing, Lynn, and Moxness 1990). Interestingly, Park, Lee, and Jeong (2018) have shown that also the past experience with noise influences how successively noise will be physiologically elaborated. Our results expand these findings showing that also a temporary state of anxiety and a negative/positive perception of the own well-being can modify the physiological response to noise.

The most interesting aspect of the present findings, however, is how psychological processes have influenced the response of the physiological system. We found that, if we are in a negative mood, small increments of acoustic noise intensity are not enough to produce a variation in physiological response. In other words, negative psychological states reduced the physiological sensitivity to noise variations. This finding could be interpreted according to the Weber's law (Weber 1978). This law, in general, states that the ability to perceive a change in the stimulus intensity decreases in proportion to its magnitude. In the present experiment, the subjective discomfort and negative mood state may have magnified the effect of the overall intensity of acoustic noise on autonomic activity. This may have led to a reduction of the overall autonomic sensitivity to variations in acoustic noise intensities. This possible generalisation of the Weber's law may be consistent with growing evidence suggesting that psychological processes, as affect and well-being state, exert direct influences on stimulus perception (Firestone & Scholl, 2016; Gerbino and Fantoni 2016). However, future studies are necessary to confirm this interpretation. A possible future development may be to investigate the possible generalisation of Weber law to other sources of environmental stimulation. In literature, there is evidence that psychological processes can influence the physiological response to other environmental stimuli, as whole-body vibration (Jalilian et al. 2019) and light (Choi et al. 2011). We could apply our experimental design to these sources of stimulation to evaluate whether a negative mood or perception of well-being have the same effect, which occurs for acoustic noise, in decreasing the physiological sensitivity to small variations in the stimulus intensities.

Future research could also be focussed on other aspects of experimental setting. First of all, it may be useful to measure other physiological parameters beside HRV. At instance, the measurement of the electrodermal activity, the respiration rate, the alterations of the blood pressure and the respiratory sinus arrhythmia can provide further indices of how noise influences the sympathetic and parasympathetic activity (Chang et al. 2009; Graham et al. 2009; Park and Lee 2017). Furthermore, it may be interesting to evaluate whether noise sensitivity or more stable personality traits (e.g. introversion/extroversion, state anxiety) have the same influence of mood in modifying the physiological sensitivity to low noise intensities. These personality traits may also correlate with the subjective perception of comfort or with the transient state mood during the noise exposure. Another issue concerns the duration of the noise exposure. We evaluated the acute physiological response to noise, but, as we have seen for other studies, the duration of the noise exposure determines different physiological responses (Park, Lee, and Jeong 2018). This aspect is relevant because the comfort experience may vary according how long the participants stay in the cabin.

5. General conclusions

Our results show that acoustic noise intensities in the range of $30-55\,\mathrm{dB(A)}$ within a ship cabin can significantly affect the perception of comfort. An increase of physiological and psychological discomfort is correlated to an increment of acoustic noise intensity. However, our findings do not confirm the existence of differences, in comfort perception, between the single comfort classes individuated by the Classification Societies. This finding suggests that comfort classes cannot be defined only as a function of the intensity of environmental stimulation. The human component is crucial to determine the real passenger's comfort experience (and this is not taken into account in the comfort class definition).

Furthermore, we found that the influence of an environmental stressor on comfort perception can strongly depend on the individual's psychological state and can be independent of the stimulus intensity. We found that this occurs when an individual is in a negative psychological state. This result suggests that, in order to provide a superior comfort service within a ship cabin, beyond the control of environmental stressors (like acoustic noise), one should consider of primary importance all services directed at the optimisation of psychological well-being state of the passenger (e.g., cruise hospitality, customised cruise solution etc).

Acknowledgments

The authors would like to acknowledge Daniel Celotti, Nicola Bassan, and Paolo Guglia from Fincantieri S.p.A. and Erina Ferro from ISTI (Istituto di Scienza e Tecnologie dell'Informazione)-National Research Council (CNR) for the support provided for the project.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study is part of Project AGORA' (E-Cabin), a Research and Innovation project in the naval sector coordinated by Fincantieri S.p.A. with the participation of the National Research Council (CNR) and the University of Trieste; the project received grants from the Italian Ministry of Infrastructures and Transport (MIT).

ORCID

Martina Lorenzino http://orcid.org/0000-0002-3271-0264

References

Bates, D. 2010. *lme4: Mixed-Effects Modeling with R*. New York: Springer.

Bates, Douglas, Martin Mächler, Ben Bolker, and Steve Walker. 2015. "Fitting Linear Mixed-Effects Models Using lme4." *Journal of Statistical Software* 67 (1): 1–48. doi:10.18637/jss.v067.i01.

Björ, B., L. Burström, M. Karlsson, T. Nilsson, U. Näslund, and U. Wiklund. 2007. "Acute Effects on Heart Rate Variability When Exposed to Hand Transmitted Vibration and Noise." *International Archives of Occupational and Environmental Health* 81 (2): 193–199. doi:10.1007/s00420-007-0205-0.

Blanchet, A. 2000. "Comfort Class and Passengers Ships." Proceedings of the 29th International Congress on Noise Control Engineering (Internoise 2000), August 27–30, Nice, France.

Cajochen, Christian, Mirjam Münch, Szymon Kobialka, Kurt Kräuchi, Roland Steiner, Peter Oelhafen, Selim Orgül, and Anna Wirz-Justice. 2005. "High Sensitivity of Human Melatonin, Alertness, Thermoregulation, and Heart Rate to Short Wavelength Light." *The Journal of Clinical Endocrinology and Metabolism* 90 (3): 1311–1316. doi:10.1210/jc.2004-0957.

Chang, T. Y., Y. A. Lai, H. H. Hsieh, J. S. Lai, and C. S. Liu. 2009. "Effects of Environmental Noise Exposure on Ambulatory Blood Pressure in Young Adults." *Environmental Research* 109 (7): 900–905. doi:10.1016/j.envres.2009.05.008.

Chida, Y., and M. Hamer. 2008. "Chronic Psychosocial Factors and Acute Physiological Responses to Laboratory-Induced Stress in Healthy Populations: A Quantitative Review of 30 Years of Investigations." *Psychological Bulletin* 134 (6): 829–885. doi:10.1037/a0013342.

Choi, C.,. K. Kim, C. Kim, S. Kim, and W. Choi. 2011. "Reactivity of Heart Rate Variability after Exposure to Colored Lights in Healthy Adults with Symptoms of Anxiety and Depression." *International Journal of Psychophysiology* 79 (2): 83–88. doi:10.1016/j.ijpsycho.2010.09.011.

Cole, Raymond J., John Robinson, Zosia Brown, and Meg O'shea. 2008. "Re-Contextualizing the Notion of Comfort." *Building Research & Information* 36 (4): 323–336. doi:10.1080/09613210802076328.

Damasio, A., and G. B. Carvalho. 2013. "The Nature of Feelings: Evolutionary and Neurobiological Origins." *Nature Reviews. Neuroscience* 14 (2): 143–152. doi:10.1038/nrn3403.

Ellermeier, W., W. Westphal, and M. Heidenfelder. 1991. "On the "Absoluteness" of Category and Magnitude Scales of Pain." *Perception & Psychophysics* 49 (2): 159–166. doi:10.3758/BF03205035.

Fantoni, C., and W. Gerbino. 2014. “Body Actions Change the Appearance of Facial Expressions.” *PLoS One* 9 (9): e108211. doi:10.1371/journal.pone.0108211.

Faul, F.,. E. Erdfelder, A.G. Lang, and A. Buchner. 2007. “G*Power 3: A Flexible Statistical Power Analysis Program for the Social, Behavioral, and Biomedical Sciences.” *Behavior Research Methods 39* (2): 175–191. doi:10.3758/BF03193146.

Firestone, C., and B. J. Scholl. 2016. “Cognition Does Not Affect Perception: Evaluating the Evidence for “top-down” effects .” *The Behavioral and Brain Sciences* 39: e229. doi:10.1017/S0140525X15000965.

Fredrickson, B., and R.W. Levenson. 1998. “Positive Emotions Speed Recovery from the Cardiovascular Sequelae of Negative Emotions.” *Cognition & Emotion* 12 (2): 191–220. doi:10.1080/026999398379718.

Fredrickson, B. L., R. A. Mancuso, C. Branigan, and M. M. Tugade. 2000. “The Undoing Effect of Positive Emotions.” *Motivation and Emotion* 24 (4): 237–258. doi:10.1023/A:1010796329158.

Gerbino, W., and C. Fantoni. 2016. “Action Valence and Affective Perception.” *The Behavioral and Brain Sciences* 39: e243. doi:10.1017/S0140525X15002605.

Goujard, B., A. Sakout, and V. Valeau. 2005. “Acoustic Comfort on Board Ships: An Evaluation Based on a Questionnaire.” *Applied Acoustics* 66 (9): 1063–1073. doi:10.1016/j.apacoust.2005.01.001.

Graham, J. M., S. A. Janssen, H. Vos, and H. M. Miedema. 2009. “Habitual Traffic Noise at Home Reduces Cardiac Parasympathetic Tone during sleep.” *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology* 72 (2): 179–186. doi:10.1016/j.ijpsycho.2008.12.004.

Green, P., and C. J. MacLeod. 2016. “SIMR: An R Package for Power Analysis of Generalized Mixed Models by Simulation.” *Methods in Ecology and Evolution* 7 (4): 493–498. doi:10.1111/2041-210X.12504.

Griefahn, B., P. Bröde, A. Marks, and M. Basner. 2008. “Autonomic Arousals Related to Traffic Noise During Sleep.” *Sleep* 31 (4): 569–577. doi:10.1093/sleep/31.4.569.

Grove, J. R., and H. Prapavessis. 1992. “Preliminary Evidence for the Reliability and Validity of an Abbreviated Profile of Mood States.” *International Journal of Sport Psychology 23*: 93–109.

Guski, R. 1999. “Personal and Social Variables as co-Determinants of Noise Annoyance.” *Noise & Health* 1 (3): 45–56.

Huang, J., F. Deng, S. Wu, H. Lu, Y. Hao, and X. Guo. 2013. “The Impacts of Short-Term Exposure to Noise and Traffic-Related Air Pollution on Heart Rate Variability in Young Healthy Adults.” *Journal of Exposure Science & Environmental Epidemiology* 23 (5): 559–564. doi:10.1038/jes.2013.21.

Hughes, J.W., and C. M. Stoney. 2000. “Depressed Mood is Related to High-Frequency Heart Rate Variability during Stressors.” *Psychosomatic Medicine* 62 (6): 796–803. doi:10.1097/00006842-200011000-00009.

Idrobo-Ávila, Ennio H., Humberto Loaiza-Correa, Leon van Noorden, Flavio G. Muñoz-Bolaños, and Rubiel Vargas-Cañas. 2018. “Different Types of Sounds and Their Relationship with the Electrocardiographic Signals and the Cardiovascular System – Review.” *Frontiers in Physiology* 9: 525. doi:10.3389/fphys.2018.00525.

Jalilian, H., Z. Zamanian, O. Gorjizadeh, S. Riaei, M.R. Monazzam, and M. Abdoli-Eramaki. 2019. “Autonomic Nervous System Responses to Wholebody Vibration and Mental Workload: A Pilot Study.” *The International Journal of Occupational and Environmental Medicine* 10 (4): 174–184. doi:10.15171/ijoem.2019.1688.

Kaczmarek, Lukasz D., Maciej Behnke, Michał Kosakowski, Jolanta Enko, Martyna Dziekan, Jaroslaw Piskorski, Brian M. Hughes, and Przemysław Guzik. 2019. “High-Approach and Low-Approach Positive Affect Influence Physiological Responses to Threat and anger.” *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology* 138: 27–37. doi:10.1016/j.ijpsycho.2019.01.008.

Kliegl, R., P. Wei, M. Dambacher, M. Yan, and X. Zhou. 2010. “Experimental Effects and Individual Differences in Linear Mixed Models: estimating the Relationship Between Spatial, Object, and Attraction Effects in Visual Attention.” *Frontiers in Psychology* 1: 238. doi:10.3389/fpsyg.2010.00238.

Kraus, Ute, Alexandra Schneider, Susanne Breitner, Regina Hampel, Regina Rückerl, Mike Pitz, Uta Geruschkat, Petra Belcredi, Katja Radon, and Annette Peters. 2013. “Individual Daytime Noise Exposure during Routine Activities and Heart Rate Variability in Adults: A Repeated Measures Study.” *Environmental Health Perspectives* 121 (5): 607–612. doi:10.1289/ehp.1205606.

Kreibig, S. D. 2010. “Autonomic Nervous System Activity in Emotion: A review.” *Biological Psychology* 84 (3): 394–421. doi:10.1016/j.biopsycho.2010.03.010.

Kwortnik, R. J., from Cornell University. 2008. Shipscape influence on the leisure cruise experience. [Electronic version]. Retrieved, School of Hotel Administration.

LeDoux, J. 2012. “Rethinking the Emotional Brain.” *Neuron* 73 (4): 653–676. doi:10.1016/j.neuron.2012.02.004.

Lee, G. S., M. L. Chen, and G. Y. Wang. 2010. “Evoked Response of Heart Rate Variability Using Short-Duration White Noise.” *Autonomic Neuroscience* 155 (1–2): 94–97. doi:10.1016/j.autneu.2009.12.008.

Liu, H., Z. Lian, Z. Gong, Y. Wang, and G. Yu. 2018. “Thermal Comfort, Vibration, and Noise in Chinese Ship Cabin Environment in Winter Time.” *Building and Environment* 135: 104–111. doi:10.1016/j.buildenv.2018.02.041.

Liu, W., Z. Lian, and Y. Liu. 2008. “Heart Rate Variability at Different Thermal Comfort Levels.” *European Journal of Applied Physiology* 103 (3): 361–366. doi:10.1007/s00421-008-0718-6.

Malik, M., J. T. Bigger, A. J. Camm, R. E. Kleiger, A. Malliani, A. J. Moss, and P. J. Schwartz. 1996. “Heart Rate Variability: standards of Measurement, Physiological Interpretation and Clinical Use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology.” *European Heart Journal* 17 (3): 354–381. doi:10.1111/j.1542-474X.1996.tb00275.x.

Mendes, W. B., and J. Park. 2014. “Chapter Six - Neurobiological Concomitants of Motivational States.” *Advances in Motivation Science* 1: 233–270.

Monazzam, M. R., E. Shoja, S. A. Zakerian, A. R. Foroushani, M. Shoja, M. Gharaee, and A. Asgari. 2018. “Combined

Effect of Whole-Body Vibration and Ambient Lighting on Human Discomfort, Heart Rate, and Reaction Time." *International Archives of Occupational and Environmental Health* 91 (5): 537–545. doi:10.1007/s00420-018-1301-z.

Nassur, Ali-Mohamed, Damien Léger, Marie Lefèvre, Maxime Elbaz, Fanny Mietlicki, Philippe Nguyen, Carlos Ribeiro, Matthieu Sineau, Bernard Laumon, and Anne-Sophie Evrard. 2019. "Effects of Aircraft Noise Exposure on Heart Rate during Sleep in the Population Living Near Airports." *International Journal of Environmental Research and Public Health* 16 (2): 269–212. doi:10.3390/ijerph16020269.

Nolich, M., D. Spoladore, S. Carciotti, R. Buqi, and M. Sacco. 2019. "Cabin as a Home: A Novel Comfort Optimization Framework for IoT Equipped Smart Environments and Application on Cruise Ships." *Sensors* 19 (5): 1060. doi:10.3390/s19051060.

Ortiz, Marco A., Stanley R. Kurvers, and Philomena M. Bluyssen. 2017. "A Review of Comfort, Health, and Energy Use: Understanding Daily Energy Use and Wellbeing for the Development of a New Approach to Study Comfort." *Energy and Buildings* 152: 323–335. doi:10.1016/j.enbuild.2017.07.060.

Park, J., S. Chung, J. Lee, J. H. Sung, S. W. Cho, and C. S. Sim. 2017. "Noise Sensitivity, Rather than Noise Level, Predicts the Non-Auditory Effects of Noise in Community Samples: A Population-Based Survey." *BMC Public Health* 17 (1): 315. doi:10.1186/s12889-017-4244-5.

Park, S. H., and P. J. Lee. 2017. "Effects of Floor Impact Noise on Psychophysiological Response." *Building and Environment* 116: 173–181. doi:10.1016/j.buildenv.2017.02.005.

Park, S. H., P. J. Lee, and J. H. Jeong. 2018. "Effects of Noise Sensitivity on Psychophysiological Responses to Building Noise." *Building and Environment* 136: 302–311. doi:10.1016/j.buildenv.2018.03.061.

Passchier-Vermeer, W., and W. F. Passchier. 2000. "Noise Exposure and Public Health." *Environmental Health Perspectives* 108 (suppl 1): 123–131. doi:10.2307/3454637.

Pressman, S. D., B. N. Jenkins, and J. T. Moskowitz. 2019. "Positive Affect and Health: What Do We Know and Where Next Should We Go?" *Annual Review of Psychology* 70: 627–650. doi:10.1146/annurev-psych-010418-102955.

Radstaak, M., S. A. E. Geurts, J. F. Brosschot, A. H. N. Cillessen, and M. A. J. Kompier. 2011. "The Role of Affect and Rumination in Cardiovascular Recovery from Stress." *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology* 81 (3): 237–244. doi:10.1016/j.ijpsycho.2011.06.017.

Rigutti, S., C. Fantoni, and W. Gerbino. 2015. "Web Party Effect: A Cocktail Party Effect in the Web Environment." *PEERJ* 3: e828. doi:10.7717/peerj.828.

Satterthwaite, F. E. 1946. "An Approximate Distribution of Estimates of Variance Components." *Biometrics Bulletin* 2 (6): 110–114. doi:10.2307/3002019.

Scarinzi, G., L. Bregant, and M. Biot. 2018. "Survey Procedures and Class Notation Harmonization for an Effective Quantification of Passenger Comfort." In *Proceedings of the NAV 2018: 19th International Conference on Ship and Maritime Research*. Amsterdam, The Netherlands: IOS Press.

Schäfer, A., and K. W. Kratky. 2006. "The Effect of Colored Illumination on Heart Rate Variability." *Forschende Komplementarmedizin (2006)* 13 (3): 167–173. doi:10.1159/000092644.

Schreiber, C. A., and D. Kahneman. 2000. "Determinants of the Remembered Utility of Aversive Sounds." *Journal of Experimental Psychology. General* 129 (1): 27–42. doi:10.1037/0096-3445.129.1.27.

Seidler, Andreas, Janice Hegewald, Anna Lene Seidler, Melanie Schubert, Mandy Wagner, Patrik Dröge, Eva Haufe, Jochen Schmitt, Enno Swart, and Hajo Zeeb. 2017. "Association Between Aircraft, Road and Railway Traffic Noise and Depression in a Large Case-Control Study Based on Secondary Data." *Environmental Research* 152: 263–271. doi:10.1016/j.envres.2016.10.017.

Sim, C. S., J. H. Sung, S. H. Cheon, J. M. Lee, J. W. Lee, and J. Lee. 2015. "The Effects of Different Noise Types on Heart Rate Variability in Men." *Yonsei Medical Journal* 56 (1): 235–243. doi:10.3349/ymj.2015.56.1.235.

Standing, L., D. Lynn, and K. Moxness. 1990. "Effects of Noise Upon Introverts and Extroverts." *Bulletin of the Psychonomic Society* 28 (2): 138–140. doi:10.3758/BF03333987.

Terry, P. C., A. M. Lane, and G. J. Fogarty. 2003. "Construct Validity of the Profile of Mood States –Adolescents for Use with Adults." *Psychology of Sport and Exercise* 4 (2): 125–139. doi:10.1016/S1469-0292(01)00035-8.

Terry, P. C., A. M. Lane, H. J. Lane, and L. Keohane. 1999. "Development and Validation of a Mood Measure for Adolescents." *Journal of Sports Sciences* 17 (11): 861–872. doi:10.1080/026404199365425.

Versfeld, N. J., and J. Vos. 1997. "Annoyance Caused by Sounds of Wheeled and Tracked Vehicles." *The Journal of the Acoustical Society of America* 101 (5 Pt 1): 2677–2685. doi:10.1121/1.418556.

Vonesh, E.F., V.M. Chinchilli, and K. Pu. 1996. "Goodness-of-Fit in Generalized Nonlinear Mixed-Effects Models." *Biometrics* 52 (2): 572–587. doi:10.2307/2532896.

Walker, E. D., A. Brammer, M. G. Cherniack, F. Laden, and J.M. Cavallari. 2016. "Cardiovascular and Stress Response to Short-Term Noise Exposures – a Panel Study in Healthy Males." *Environmental Research* 150: 391–397. doi:10.1016/j.envres.2016.06.016.

Wang, H., and L. Liu. 2020. "Experimental Investigation About Effect of Emotion State on People's Thermal Comfort." *Energy & Buildings* 211: 109789. doi:10.1016/j.enbuild.2020.109789.

Weber, E. H. 1978. *The Sense of Tourch.* 1st ed. London: Academic Press.

Zhang, N., M. Fard, M. H. U. Bhuiyan, D. Verhagen, M. F. Azari, and S. R. Robinson. 2018. "The Effects of Physical Vibration and Heart Rate Variability as a Measure of Drowsiness." *Ergonomics* 61 (9): 1259–1272. doi:10.1080/00140139.2018.1482373.