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Acute stress effects of impulsive noise during mental work

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ABSTRACT

Impulsive sound has been found to annoy people more than steady-state sound or many other types of sound presented at the same sound level. This study examined the physiological, performance, and subjective effects of impulsive sound on working humans. Exposure to impulsive sound (65 dB L_{Aeq}) was compared with quiet sound (35 dB L_{Aeq}) and steady-state sound (65 dB L_{Aeq}). This parallel-group study, where each participant was exposed to one sound condition, had altogether 59 participants. Physiological stress was measured with stress hormone concentrations in plasma (cortisol and noradrenaline), heart rate variability (HRV), and blood pressure. Psychological stress was measured with subjective noise annoyance, workload, and fatigue. Performance was measured in tasks requiring constant concentration (visual and auditory serial recall and N-back). Compared to quiet sound, impulsive sound caused more annoyance, workload, and lack of energy, raised cortisol concentrations, reduced systolic blood pressure, and decreased accuracy in the 3-back task. Compared with steady-state sound, impulsive sound was experienced as more annoying and causing a higher workload and more lack of energy. Impulsive sound caused physiological and psychological stress and decreased performance compared to quiet sound. Part of this load was due to the increased sound level, which was evident as a physiological stress reaction. Still, there was also an extra stress effect related to the impulsiveness of the sound, reflected as a psychological experience. Special care should be paid to impulsive sound, especially in environments where people are performing mental work.

1. Introduction

Excessive noise is a serious environmental stressor in many living environments. Environmental noise was estimated to have the second highest adverse public health impact of nine environmental risk factors in a study conducted across six European countries (Hänninen et al., 2014). At moderate levels, noise does not endanger one's hearing but may have non-auditory adverse effects, such as feelings of annoyance, disturbed sleep, impairment of learning in children, and an increased risk for ischemic heart disease (World Health Organization, 2011, 2018). From these adverse effects of sound, annoyance was estimated to be the second major health effect of environmental noise in Europe after sleep disturbance (World Health Organization, 2011).

Annoyance can be measured using, e.g., 11-step numerical response scale (0 Not at all annoyed, 10 Extremely annoyed) (ISO, 2003). Those who respond 8 or more, are considered as highly annoyed. High annoyance caused by different types of environmental noise has been widely investigated (e.g. Guski et al., 2017). Associations between sound levels and high annoyance are described with exposure-response relationships. They are different for road traffic, air traffic, and wind turbine noise, for example (Guski et al., 2017; Janssen et al., 2011). Furthermore, different exposure-response relationships have been found in different countries or areas (Miedema & Vos, 1998). Thus, sound level alone is an insufficient variable to explain high annoyance.

Other acoustic and non-acoustic characteristics of sound also influence the perceived annoyance. Basic sound characteristics that have been reported to increase annoyance ratings at constant sound levels in controlled laboratory experiments include, at least, tonality (Oliva et al., 2017), impulsivity (Rajala & Hongisto, 2020), spectrum (Hongisto et al., 2015), and amplitude modulation (Virjonen et al., 2019). These observations stem from so-called focused psychoacoustic experiments where participants' only task was to listen and rate the annoyance of sounds using the 11-step response scale. In our study, we sought to gain understanding on the effects of impulsive sound in a broader context, where the participants would not be focused on the sound stimulus but would be performing different cognitively demanding tasks during

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sound exposure.

Impulsive sound means that the time profile of the sound level involves strong onsets, i.e., rapid elevations of the sound level, and a release of sound right after the impulse has reached its maximum. Impulsive sounds in daily environments are numerous, since the dropping, hitting, slamming, and rattling of objects produce impulses. Typical examples in everyday life are walking, door sounds, ball games, keyboard tapping, and hammering. Speech and music also contain impulsive components, but they are seldom treated as impulsive sound, and are rather classified as sound with high information content. Since sounds contain frequencies from a broad range, from 20 to 20 000 Hz, and human hearing has a specific and well-known sensitivity to different frequencies, frequency weighting A is usually applied to describe the objective loudness of sound with a single value (IEC, 2013). This is called the A-weighted sound pressure level (SPL), L_{Aeq}, where “eq” (equivalent) refers to time-averaged value. Rajala and Hongisto (2020) have shown that an impulsive sound can be significantly more annoying than a steady-state sound, when presented at similar L_{Aeq} values. They found that a steady state sound could be presented even 8 dB louder to have the same annoyance as an impulsive sound had. This difference is called penalty, k [dB]. The rating level, $L_{\mathrm{Aeq}} + k$ describes annoyance better than L_{Aeq}. The penalty of impulsive sound increased with increasing onset rate and level difference. The determination of these quantities for a single impulse are described in Fig. 1.

Annoyance is the most prevalent non-auditory effect of environmental noise (Basner et al., 2014). However, due to its subjective nature, annoyance estimations have large interpersonal variations. Annoyance is often accompanied by an acute physiological stress reaction, which gives a more objective estimation of stress level. Acute stress reactions to noise may be reflected, e.g., as increased circulating stress hormone concentrations (Babisch, 2003; Radun et al., 2021) and altered heart rate variability (HRV) (Idrobo-Ávila et al., 2018; Radun et al., 2021). Also objective estimations have large interpersonal variations. Therefore, to understand better the effects of a special sound characteristic on human, a combination of annoyance and acute physiological responses is highly justified.

Exposure to sounds might cause acute physiological stress reaction reflected in the cardiovascular system. The SPL of white noise (50—80 dB L_{Aeq}) correlated with changes in HRV (Lee et al., 2010). White noise presented at 85 dB L_{Aeq} influenced HRV compared to no exposure indicating a physiological stress response (Björ et al., 2007). Industrial noise exposure at 95 dB was related to increased diastolic blood pressure and mean arterial pressure compared to 40 dB noise (Andrén et al., 1982). The cited studies applied quite high sound levels ($\geq$80 dB L_{Aeq}). Therefore, they may have little relevance for residential environments. Furthermore, hearing protection is expected to be employed in, e.g., workplaces where the sound level exceeds 80 dB L_{Aeq} in European Union member states (EU, 2003).

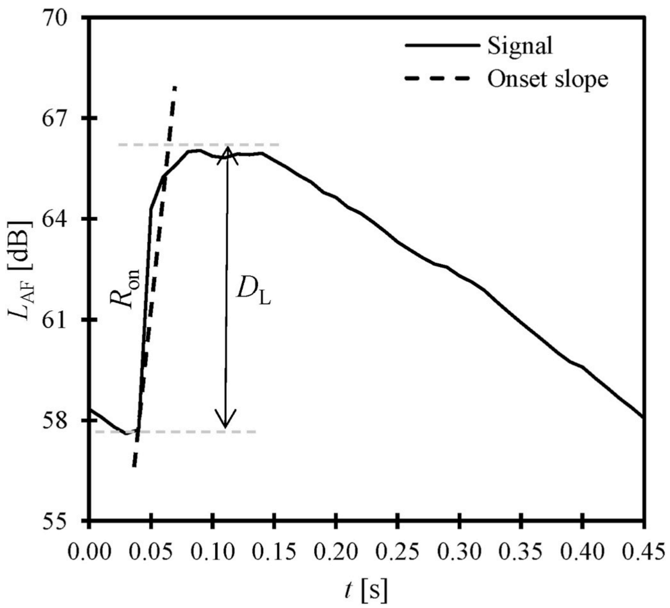

Fig. 1. Fast-time weighted SPL, L_{AF}, of a single impulse as a function of time, t, for a single impulse. The sampling time is 10 ms. Level difference, D_{L} [dB], and onset rate, R_{on} [dB/s], describe the strength and abruptness of the impulse. Fast corresponds to the reaction speed of hearing to rapid changes in sound (IEC, 2013).

Exposure to noise during one’s current task might also elevate stress and be reflected to endocrine system. For example, when a person was solving arithmetic calculations during high sound levels (90 dB L_{Aeq}) of white noise, cortisol levels were higher than during a quieter sound condition (55–60 dB L_{Aeq}) (Miki et al., 1998). Random bursts of intermittent background noise at 90 dB L_{Aeq} consisting of superimposed traffic, office machinery, and unintelligible speech caused increased heart rate and higher circulating cortisol and noradrenaline levels when compared with quieter condition of 45 dB L_{Aeq}, but only in a high-effort situation (Tafalla & Evans, 1997). Furthermore, performing tasks under intermittent noise of 99 dB L_{Aeq} has been linked to slightly amplified cortisol responses compared with the response of 45 dB L_{Aeq} noise (Brandenberger et al., 1980). However, only performing the tasks triggered the higher cortisol response than a control condition without noise and task (Brandenberger et al., 1980).

Both exposure to noise without a task and performing tasks in the absence of noise cause independently physiological reactions. Resource-based models of performance under stress, such as compensatory control model (Robert & Hockey, 1997) and maximal adaptability model (Hancock & Warm, 1989), have explained the influence of different noise types on performance the best (Szalma & Hancock, 2011). These models state that to a working person, noise exposure can cause an additional workload when the person must increase the effort to maintain his/her performance at the same level as without the sound. Using strong efforts increases stress to such an amount that it can be observed using physiological stress meters. Low effort may only reflect on subjective responses such as feelings of annoyance and increased workload. In addition, the extra effort may not suffice to compensate for the negative impact of the disturbance, and sound can also impair performance. The magnitude of this impairment depends both on the sound and task types (Szalma & Hancock, 2011).

Our aim was to evaluate the acute effects of impulsive sound on healthy human participants performing tasks requiring constant concentration and working memory processing. To extract the pure effect of impulsivity, the effects of steady-state noise, carrying the same sound energy as the impulsive sound stimulus were also assessed. Therefore, our experiment involved impulsive sound (65 dB L_{Aeq}), steady-state sound (65 dB L_{Aeq}), and quiet sound (35 dB L_{Aeq}) with average exposure time of 49 min. Based on current knowledge, we set hypotheses in the following way:

H1. Impulsive sound causes a large negative effect compared to quiet sound;

H2. Steady-state sound causes a small negative effect compared to quiet sound;

H3. Impulsive sound causes a small negative effect compared to steady-state sound.

If the difference in stress effect is large, then the effects are expected to be seen in all types of responses, i.e., psychological, physiological, and performance as stated by resource-based models of performance under stress (Robert & Hockey, 1997; Szalma & Hancock, 2011). Small stress effects may not influence performance, since people will be able to compensate for the effects of noise by putting in more effort (Robert & Hockey, 1997). Small stress effects may only become evident as psychological effects, but also signs of a physiological stress response may be seen.

2. Materials and methods

2.1. Design

A medical laboratory experiment was conducted with a parallel-group design, where each group was exposed to one of the three investigated sound conditions. The experiment involved three *sound conditions*: quiet sound, steady-state sound, and impulsive sound. The exposure time for each *sound condition* was the same. Gender and noise sensitivity were used to stratify the participants into three balanced groups.

2.2. Participants

A total of 61 voluntary adult participants were enrolled in the study. The inclusion criteria and the instructions given to the participants before the experiment are presented in the Supplementary material Sec. S1.1. Data of one participant was excluded from analyzes due to impaired hearing in the hearing test. One participant fainted in connection with venous cannulation and discontinued the participation. The final number of participants was thus 59 (39 women, mean age 24.8 years, range 20–42 years).

2.3. Ethical aspects

The Ethical Committee of the Hospital District of Southwest Finland approved the study (ETMK Dnro 20/1801/2018). All participants provided voluntary informed consent before participation. The participants were compensated for their effort and time with a gift voucher worth 70 Euro.

2.4. Sound condition groups

The sound condition groups were formed to include both men and women and they were balanced according to the *noise sensitivity* score of each participant. The participants filled Weinstein's 21-item *noise sensitivity* scale (Weinstein, 1978) while registering for the experiment. *Noise sensitivity* classification was performed using data collected from five previous laboratory experiments (N = 184). The data are presented in the Supplementary material Sec. S1.2. The respondents were divided into tertiles defined by the following cut-off scores: the maximum score for the low-sensitivity group was 73 points; the minimum score for the high-sensitivity group was 87 points; and scores from 74 to 86 belonged to the middle-sensitivity group. These noise sensitivity groups were only used to divide the participants into *sound conditions* in the recruitment phase. The participants were allocated to different *sound conditions* according to their gender, noise sensitivity score, and the date they could participate. Table 1 shows the division of participants into the *sound condition* groups.

The sample size of the groups was based on previously published results; the group sizes of previous similar studies have typically ranged from 8 to about 20 (Brandenberger et al., 1980; Evans & Johnson, 2000; Miki et al., 1998; Sim et al., 2015). We aimed to include 18 fully evaluable participants in each group. Since the sample size was not determined by power calculations, the sensitivity of our analysis was defined for 60 participants across three groups with 80% power (alpha = 0.05) using software package G*Power 3.1.9.7 (Faul et al., 2007). An analysis of variance (ANOVA) would be sensitive to effects of $\eta_p^2 = 0.14$ and mixed model analysis of variance (mANOVA) to effect sizes of $\eta_p^2 = 0.13$ with 2 or 4 repetitions and correlation among repeated measures 0.8. This means the study would not be able to reliably detect effects smaller than these values that correspond to the limit of large effects $\eta_p^2 = 0.14$ (Cohen, 1988).

Table 1
The number of participants in the different *sound condition groups* and their division into three *noise sensitivity* (NS) categories. The number of participants from whom all blood samples were obtained are presented in brackets. The missing blood samples were due to blocked catheters.

Sound condition	High NS	Middle NS	Low NS	Total
Quiet sound	4 (4)	7 (5)	8 (6)	19 (15)
Steady-state sound	5 (4)	7 (6)	7 (6)	19 (16)
Impulsive sound	4 (3)	8 (4)	9 (8)	21 (15)
Total	13 (11)	22 (15)	24 (20)	59 (46)

2.5. Experimental setting

The experimental room is presented in the Supplementary material Sec. S1.3.

2.6. Description of the sound conditions

Table 2 gives the objective descriptors of the *sound conditions*, and Fig. 2 illustrates the spectra (a) and time profiles (b).

All sounds were edited using Adobe Audition 3.0 (Adobe Inc., San Jose, California, USA) and MATLAB R2017b (The MathWorks Inc., Natick, Massachusetts, USA). Steady-state sound was created from pseudorandom pink noise with Graphical Equalizer in Adobe Audition. Quiet sound was created from steady-state sound by decreasing the SPL by 30 dB. Quiet sound was set to 35 dB L_{Aeq}, which was 10 dB above the background SPL of the room, 25 dB L_{Aeq}. Artificial sound was used to produce the *sound condition* Quiet sound because the background SPL of the experimental room (25 dB L_{Aeq}) was considered too silent, as sounds produced by the investigators and participants could have become audible. 35 dB is a typical target level of ventilation noise in offices, schools, and hospitals. Therefore, 35 dB sound level (corresponds to *sound condition* Quiet sound) was always present in the room, except when the experimental sound was on.

Impulsive sound was obtained from an outdoor recording at a construction site where pile driving was being carried out. Each onset caused by the pile impact causes a sharp and distinctive onset of sound level (average onset rate 236 dB/s; Table 2). People rate this kind of sound highly impulsive. The original recording was short, and it was multiplied to a 90 min long audio file, so that the looping section was inaudible.

The *sound conditions* were presented within one-third octave bands from 100 to 10 000 Hz. The experimental sounds were band-pass filtered using an 80th order Butterworth filter with cut-off frequencies of 89 and 10 500 Hz and stop-band attenuation of 60 dB. All sounds were saved as mono wav-files (16 bit, 44 100 Hz).

Table 2
The objective descriptors of the *sound conditions*. An empty value means that this acoustic property was not relevant for this *sound condition*.

	D_L[a]	R_{on}[a]	L_{A5}—L_{A95}[b]	L_{Aeq}[c]
Sound condition	[dB]	[dB/s]	[dB]	[dB]
Quiet sound	–	–	1.0	35
Steady-state sound	–	–	1.0	65
Impulsive sound	8.2	236.2	8.8	65

[a] Impulsive properties of sound are measured according to the Nordtest method NT ACOU 112 (Nordtest, 2002). The descriptive quantities are level difference, D_L, which describes the strength of the impulse, and onset rate, R_{on}, which expresses how fast the impulse grows.

[b] Variability of sound was described by the difference of 5% and 95% percentiles of A-weighted SPL, L_{A5}—L_{A95}, using Fast time weighting.

[c] A-weighted equivalent SPL, L_{Aeq}, corresponds to the whole duration of the experimental phase, lasting typically 50 min.

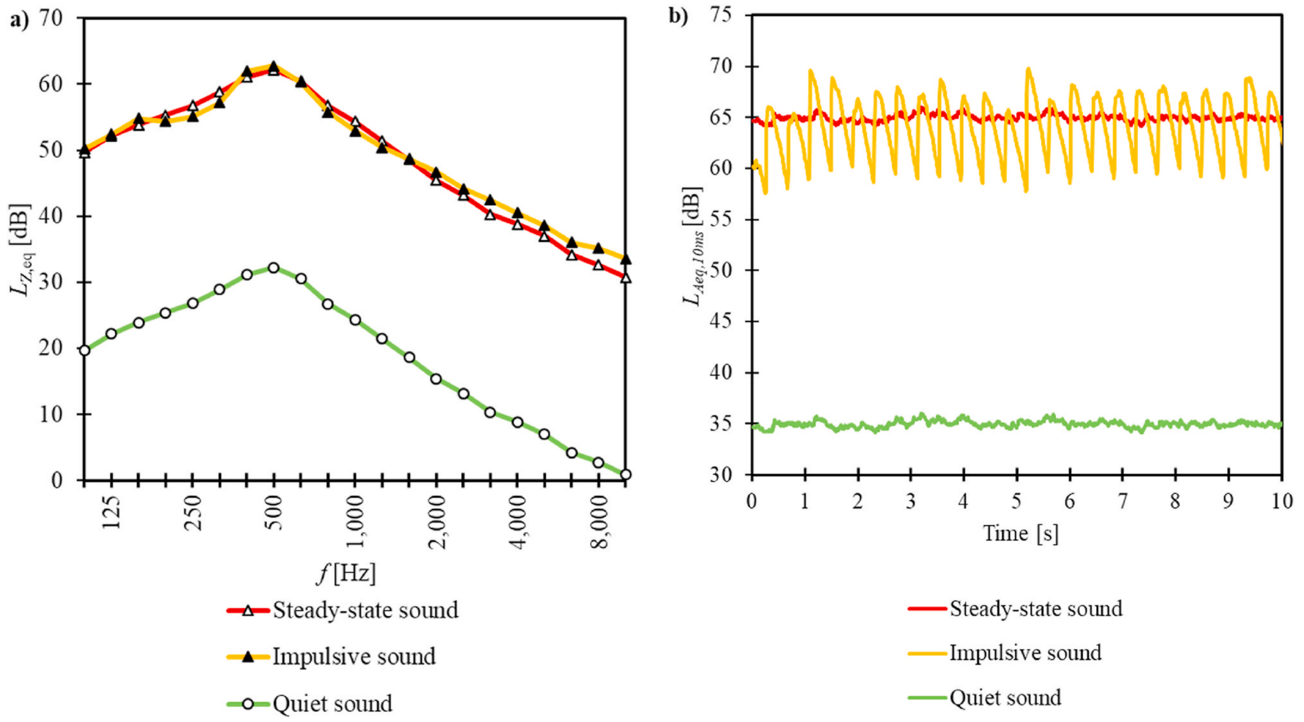

Fig. 2. (a) The unweighted equivalent SPL, $L_{Z,eq}$, as a function of the sound frequency, f, for the three *sound conditions*. (b) The A-weighted equivalent SPL, $L_{A,eq,10\ ms}$, as a function of time during a typical 10-s slice of the *sound condition*. The time profile was based on 10 ms time resolution. The equivalent SPLs during the 10-s samples, $L_{Aeq,10s}$, correspond to the values for the whole test phase when the experimental sound was on.

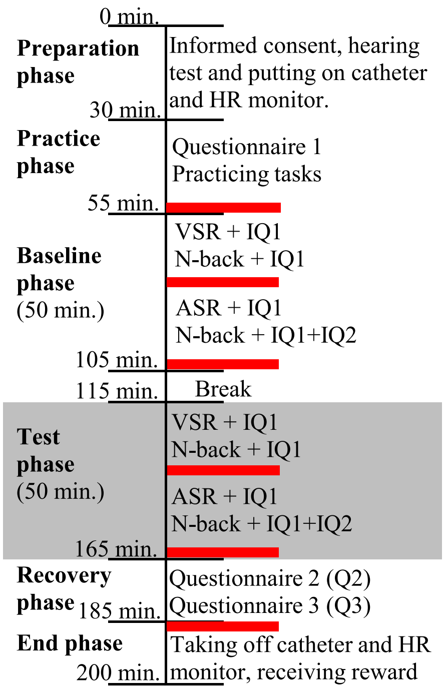

Fig. 3. Procedures of the experiment. The red lines indicate taking blood samples and measuring blood pressure (measurement times). The grey area indicates when the experimental sound was present. Each participant was exposed to one test phase, i.e., one *sound condition*. The minutes in brackets describe the duration of the phases and minutes without brackets indicate the timeline of the experiment. Q = Questionnaire, IQ=Intermediate Questionnaire, VSR=Visual Serial Recall, ASR = Auditory Serial Recall, HR=Heart rate. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The spectrum of sound affects annoyance (Hongisto et al., 2015). Therefore, all *sound conditions* were equalized to have equivalent spectral shapes in one-third octave bands (Fig. 2) using the Graphical Equalizer of Adobe Audition. This was made to avoid the situation that the spectrum of sound would also be an independent variable. These three spectra were in line with standardized human speech (ISO, 2012).

2.7. *Playback and measurement of sound conditions*

The sounds were played using Windows Media Player 12, a Roland Rubix 22 sound card (Roland Co., Hamamatsu, Japan), and two Genelec 8020 A active loudspeakers (Genelec Ltd., Iisalmi, Finland). The SPL in one-third octave bands of each *sound condition* was measured at four locations in the experimental room. The locations approximately corresponded to those of the subjects' ears during the experiment. The measurements were made using a sound level meter (NTi Audio XL2, NTi Audio AG, Schaan, Liechtenstein), a microphone (NTi Audio M2211, NTi Audio AG), and a preamplifier (NTi Audio MA220, NTi Audio AG). The spectra of the *sound conditions* were adjusted so that the measured spectrum in each of the four measurement locations corresponded to the target spectra shown in Fig. 2a. The acoustic analyses of Fig. 2 and Table 2 were done using MATLAB.

2.8. *Psychological variables*

The psychological dependent variables are presented in Table 3. Besides aggregated rating scales (e.g. SOFI), annoyance and workload were treated as continuous variables, since this can be done for aggregated rating scales as well as for individual rating items with numerical response formats and at least five categories (Harpe, 2015).

2.9. *Performance variables*

During the experiment, the participants performed three tasks, which were presented using MATLAB R2015a with Psychtoolbox – 3

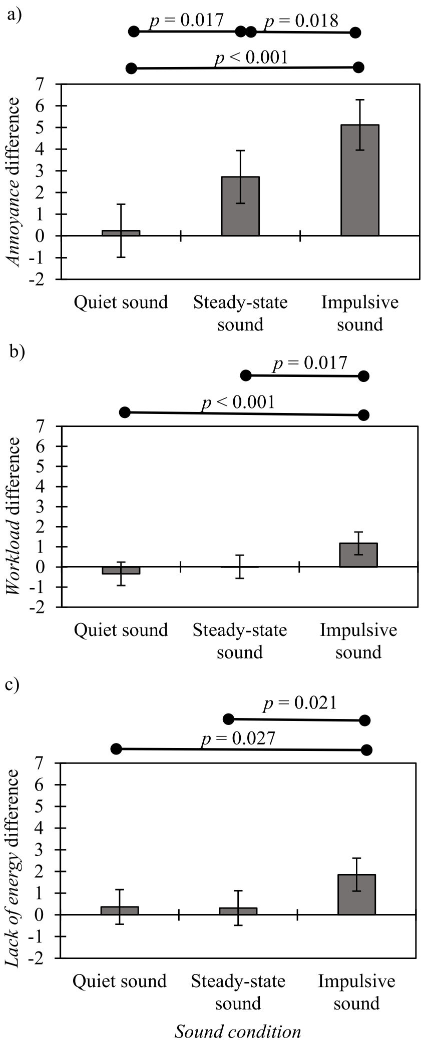

Fig. 4. Psychological measures (*annoyance*, *workload*, *lack of energy*) showing significant main effect of *sound condition*. The bars represent means and error bars 95% confidence intervals. The lines above the graphs represent statistically significant differences.

(PTB; psychtoolbox.org) (Brainard, 1997). The tasks were N-back with four variations (0, 1, 2, and 3-back), visual serial recall (VSR), and auditory serial recall (ASR). The tasks are presented in detail in the Supplementary material Sec. S1.4 and performance variables in Table 3.

2.10. Physiological variables

Stress hormones cortisol and noradrenaline were measured from venous blood utilizing a peripheral venous access catheter that was placed in the participants' forearm in the beginning of the experiment. Blood pressure (BP) was recorded with an indirect blood pressure monitor (Omron M3 Comfort, Omron Healthcare Co., Ltd., Kyoto, Japan). HRV was measured with a sensor (Faros 180, Bittium Biosignals Ltd., Kuopio, Finland) attached to the participant with a textile belt and Stingray adapter, positioned under the chest muscle line. The physiological measurements are presented in detail in the Supplementary material Sec. S1.5 and physiological variables in Table 3.

2.11. Experimental procedure

The procedure is shown in Fig. 3. Experimental sessions always started at 11.45 a.m. One or usually two participants attended each session. After arrival, the participant read and signed the informed consent form. During the preparation phase, the heart rate monitor was put on, the peripheral venous access catheter was inserted, and hearing was tested with a Screening Audiometer (Madsen Micromate 304, Otometrics, Taastrup, Denmark).

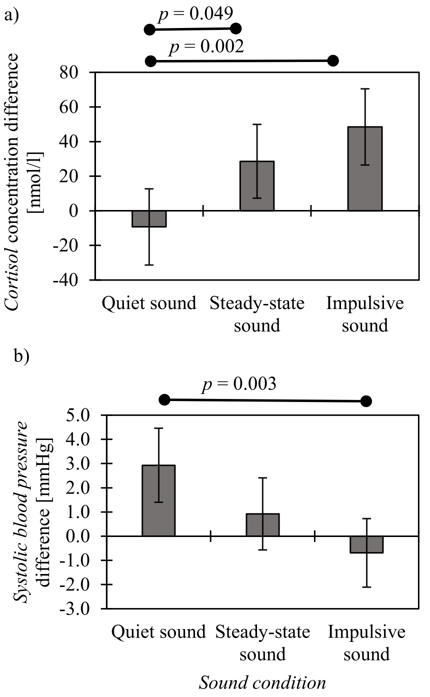

Fig. 5. Physiological measures (*cortisol*, *systolic blood pressure* SBP) showing significant main effect of *sound condition*. The bars represent means and error bars 95% confidence intervals. The lines above the graphs represent statistically significant differences.

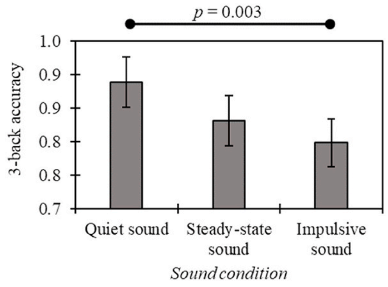

Fig. 6. Performance measures with a significant main effect on *sound condition*. Accuracy is the proportion of correct answers in 3-back task. The bars represent means and error bars 95% confidence intervals. The line above the graph represents a statistically significant difference.

The practice phase included the completion of Questionnaire 1 (Q1), and explaining and practicing all tasks one-by-one. The baseline and test phases were identical apart from the fact that the *experimental sound* was on in the test phase. The tasks were presented in the following order in both phases: *VSR*, *N-back*, *ASR*, and *N-back*. After each task, the participants filled Intermediate Questionnaire 1 (IQ1), and after the whole phase, they filled Intermediate Questionnaire 2 (IQ2). There was a break between the baseline phase and the test phase. The baseline phase lasted an average of 51 min (range, 44 min–61 min), and the test phase lasted an average of 49 min (range, 42 min–58 min), which was the same as the sound exposure time.

The recovery phase started when the *experimental sound* was changed to quiet sound, or when the fifth blood samples had been taken. During the recovery phase, participants completed a personality questionnaire (Konstabel et al., 2012) (Q2) and Questionnaire 3 (Q3), with general

Table 3
The dependent variables of the study.

Dependent variable	Name or description of variable	Response/unit	Range	Position (See Fig. 3)
Background information				
Noise sensitivity	21-item Noise sensitivity scale (Weinstein, 1978)		21–126	Recruitment questionnaire
General stress	Perceived Stress Scale PSS-10 (S. Cohen et al., 1983)		0–40	Q1
Psychological measures				
Annoyance	How much does the sound annoy, disturb, or bother you? (ISO, 2003)	0 Not at all, 10 Extremely	0–10	IQ1 & IQ2
Workload	How demanding/loading was performing the previous task in your opinion?	0 Not at all, 10 Extremely	0–10	IQ1 & IQ2
Perceived fatigue	Swedish Occupational Fatigue Inventory SOFI (Åhsberg & Gamberale, 1998)	1 Not at all, 2 Slightly, 3 To some extent, 4 Quite a lot, 5 Very much		IQ2
Tiredness	sleepy, yawning & drowsy (0.62, 0.66)[a]		3–15	
Lack of energy	worn out, exhausted, drained (0.83, 0.88)[a]		3–15	
Lack of motivation	uninterested, indifferent, passive (0.82, 0.89)[a]		3–15	
Performance measures				
N-back RT	0, 1, 2, 3-back reaction time	seconds		Twice in baseline and test phases
N-back accuracy	0, 1, 2, 3-back accuracy	Mean Accuracy	0–1	Twice in baseline and test phases
Auditory serial recall (ASR)	Remembering 9 numbers presented in random order via headphones.	Accuracy per position	0–1	Once in baseline and test phases
Visual serial recall (VSR)	Remembering 9 numbers presented in random order on display.	Accuracy per position	0–1	Once in baseline and test phases
Physiological measures				
Blood pressure				Six times during the experiment
Systolic blood pressure	Systolic blood pressure	mmHg		
Diastolic blood pressure	Diastolic blood pressure	mmHg		
HRV				Continuously measured
$HRV_{LF/HF}$	LF/HF ratio during task performance			
Stress hormone concentrations				Six times during the experiment
Cortisol	Concentration in plasma, in blood collected from a peripheral venous catheter	nmol/l		
Noradrenaline		nmol/l		

Q1 = Questionnaire 1; IQ1 = Intermediate Questionnaire 1; IQ2 = Intermediate Questionnaire 2.

[a] Cohen's alpha for the scales in baseline and test phases.

questions concerning their condition and experiences regarding the experiment. Blood sampling and recording of BP were repeated six times over the entire experiment. To control for the potential stress effect of catheter insertion, there was always at least 30 min time difference between catheter insertion and collection of the first blood samples. In addition, the last blood sample was taken at least 20 min after the end of the *experimental sound* exposure.

One experimental session lasted an average of 3 h 22 min (range: 2 h 55 min to 4 h 11 min).

2.12. Statistical analyses

Statistical analyses were conducted with IBM SPSS Statistics for Windows, Version 25 (IBM Corp., Armonk, NY, USA). S*ound condition* was always defined as the between-group variable having three levels (Quiet sound, Steady-state sound, and Impulsive sound). If this main effect was significant, pairwise comparisons between the *sound conditions* were conducted. To ensure that the distribution of dependent variable values did not differ from normal, the normality and outliers were examined with the Kolmogorov-Smirnov test of normality, and kurtosis and skewness values (between -2 and 2). If either of these conditions were met, parametric analysis was performed; in other case, outliers were examined. If the removal of one or two outliers was not enough to provide normality, non-parametric tests were used. Due to multiple comparisons examining the effects of sound, Benjamini-Hochberg procedure was used for the main effects of *sound condition* and Bonferroni correction was used for pairwise tests. Benjamini-Hochberg controls for false discovery rate, which means it takes into account that some findings might be false positives (McDonald, 2014). This means that the *p*-values of all 14 tests examining the effects of psychological, physiological and performance measures were examined with Benjamini Hochberg procedure (altogether 14 tests, see e.g. Table S2). The Benjamini-Hochberg false discovery rate was set to 0.05, that can be considered rather strict (McDonald, 2014). In the results, the raw *p*-values are reported and the significance of Benjamini-Hochberg procedure is mentioned only if it is in conflict with the raw *p*-value.

To ensure that the groups were comparable at baseline, the groups' background information as well as performance in the baseline phase was examined. For their gender distribution, the χ^2-test was used, for *age* Kruskal-Wallis H test for independent samples (not normally distributed) and other variables were compared with ANOVA or mANOVA. In *general stress*, two participants had missed one rating, which was replaced by their median value.

For the test phase's psychological and physiological variables, difference values were calculated to reduce the effect of inter-subject differences. Difference values showed the change due to the *sound condition* in relation to a reference value. The reference values were deducted from the test phase values (test phase value minus reference value). The reference value was the baseline phase value for all other psychological and physiological variables except for *cortisol*. For *cortisol*, the recovery phase value was selected as the reference value because of the diurnal variation and other variability in the *cortisol* values of the baseline phase samples. It is well-known that cortisol concentrations in plasma show strong diurnal variation, with the highest levels in the morning, and awakening time thus influences the concentrations during the day (Kudielka & Kirschbaum, 2003). For this reason, the participants were instructed to wake up the latest at 8 a.m., and all experimental sessions were conducted in the early afternoon. The changes in *cortisol* as a function of time in our experiment are presented in Figure S3 of the Supplementary material. *Cortisol* concentrations did not differ between the three *sound condition* groups in the recovery phase ($\chi^2(2) = 0.2$, $p = 0.927$, $E^2 = 0.003$). The values of the physiological variables, measured six times during the experiment, are presented as a function of time in Figures S3–S6 of the Supplementary material.

For the difference values, the parametric tests used were ANOVA or mANOVA. When there was more than one measurement of the dependent variable in the test phase, mANOVA was used with repetition (2) during the test phase as a within-subject variable, otherwise ANOVA was used. In within-subject comparisons, the Greenhouse-Geisser correction was used if sphericity could not be assumed. If the normality conditions were not met, either one outlier was removed, or non-parametric tests were used. In addition, if the measurements were repeated several times in the test phase, the distribution of the mean values was examined and used if the conditions for normality were filled.

For the performance measures, difference values were not used due to the variation in performance in the baseline phase. We hypothesized this variation reflected learning effect or excitement. Therefore, only the test phase values were examined. In *serial recall tests*, mANOVA was used with the proportion of correct answers per position (9) as the within-subject variable. For *N-back RT*, mANOVA was used, with repetition (2) and N-back level (4) as within-subject variables. In *N-back accuracy*, only the accuracy of *3-back* was distributed sufficiently normally to use mANOVA with repetition (2) as a within-subject variable. For the other versions of N-back, the Kruskal-Wallis H test for independent samples was used with Epsilon squared as the measure of effect size.

The exact results with and without including outliers are reported in the Supplementary material (Tables S1, and S2). In addition, the results with *general stress* as a covariate are reported in Table S3, but since the results are the same as without the covariate and outliers, the reported results are based on the examination without a covariate reported in Table S1. The table of the main results is presented in the Appendix Fig. A.1.

3. Results

3.1. Baseline comparisons

The *sound condition* groups did not differ from each other in terms of gender distribution ($\chi^2(2) = 4.1$, $p = 0.128$, $V = 0.264$), *age* ($\chi^2(2) = 0.0$, $p = 0.987$), *noise sensitivity* ($F(2, 56) = 1.0$, $p = 0.389$, $\eta_p^2 = 0.033$), but there was a difference in the perceived level of *general stress* ($F(2, 56) = 4.2$, p=0.018, $\eta_p^2 = 0.133$). The Impulsive sound group scored lower in *general stress* (mean = 7.4; CI 5.3—9.5) than the Steady-state sound group (mean = 11.6; CI 9.4—13.8; $p = 0.024$), but did not differ from the Quiet group (mean = 10.8; CI 8.6—13.0; $p = 0.096$). The *sound condition* groups did not differ from each other in the performance accuracy of the baseline phase (*ASR*: $F(2, 56) = 0.2$, p=0.821, $\eta_p^2 = 0.007$; *VSR*: $F(2, 56) = 0.2$, p=0.849, $\eta_p^2 = 0.006$; *3-back*: $F(2, 54) = 1.7$, p=0.199, $\eta_p^2 = 0.058$).

3.2. Psychological measures

Annoyance depended on the *sound condition* (F(2, 56) = 16.9, $p < 0.001$, $\eta_p^2 = 0.376$) (Fig. 4a). Statistically significant differences were found between all *sound condition* pairs. Quiet sound was less annoying than Steady-state sound ($t(36) = -2.7$, $p = 0.017$, $d = 0.86$) or Impulsive sound ($t(38) = -7.1$, $p < 0.001$, $d = 2.24$), and Impulsive sound was more annoying than Steady-state sound ($t(38) = -2.6$, $p = 0.018$, $d = 0.84$).

Workload was higher during Impulsive sound than during Steady-state sound ($t(38) = -3.6$, $p = 0.017$, $d = 1.13$) or Quiet sound ($t(38) = -3.5$, $p < 0.001$, $d = 1.11$) (F(2, 55) = 7.8, $p = 0.001$, $\eta_p^2 = 0.220$; Fig. 4b).

Lack of energy was also higher during Impulsive sound than during Steady-state sound ($t(38) = -2.8$, $p = 0.021$, $d = 0.89$) or Quiet sound ($t(38) = -2.7$, $p = 0.027$, $d = 0.86$) (F(2, 56) = 5.1, $p = 0.009$, $\eta_p^2 = 0.115$; Fig. 4c), but there were no statistically significant differences between the *sound conditions* in *tiredness* (F(2, 56) = 0.1, $p = 0.947$, $\eta_p^2 = 0.002$) or *lack of motivation* (F(2, 56) = 1.0, $p = 0.380$, $\eta_p^2 = 0.034$).

3.3. Physiological measures

Cortisol concentrations in plasma depended on the *sound condition* (F (2, 43) = 7.2, $p = 0.002$, $\eta_p^2 = 0.252$) (Fig. 5a). During Impulsive sound ($t(28) = -3.4$, $p = 0.002$, $d = 1.25$) and Steady-state sound ($t(29) = -2.3$, $p = 0.049$, $d = 0.81$), *cortisol* was higher than during Quiet sound. Therefore, during Quiet sound, the diurnal nadir of the day was already reached, whereas the other *sound conditions* prevented this.

Also concentrations of *noradrenaline* in plasma was affected by *sound condition* (F(2, 47) = 3.3, $p = 0.046$, $\eta_p^2 = 0.123$). However, Benjamini-Hochberg procedure for false discovery rate indicated that the effect is not significant. In addition, none of the pairwise comparisons were significant ($p > 0.05$).

Sound condition influenced also *systolic blood pressure* (F(2, 55) = 6.1, $p = 0.004$, $\eta_p^2 = 0.181$) (Fig. 5b). Impulsive sound was associated with lower *systolic blood pressure* than Quiet sound ($t(37) = 3.8$, $p = 0.003$, $d = 1.21$). *Sound conditions* did not differ from each other in *diastolic blood pressure* (F(2, 55) = 2.1, $p = 0.133$, $\eta_p^2 = 0.071$) or $\mathrm{HRV}_{\mathrm{LF/HF}}$ (F(2, 54) = 0.5, $p = 0.633$, $\eta_p^2 = 0.017$).

3.4. Performance measures

Sound condition influenced 3-back accuracy (F(2, 56) = 6.2, $p = 0.004$, $\eta_p^2 = 0.181$) (Fig. 6). The 3-back performance was lower during Impulsive sound than Quiet sound ($t(39) = 3.3$, $p = 0.003$, $d = 1.04$). In the other versions of the N-back task, the *N-back accuracy* did not differ between the *sound conditions* (1st N-back: 0-back: $\chi^2(2) = 2.0$, $p = 0.365$, $E^2 = 0.036$; 1-back: $\chi^2(2) = 1.2$, $p = 0.542$, $E^2 = 0.020$; 2-back: $\chi^2(2) = 2.1$, $p = 0.353$, $E^2 = 0.039$; 2nd N-back: 0-back: $\chi^2(2) = 0.4$, $p = 0.823$, $E^2 = 0.007$; 1-back: $\chi^2(2) = 0.6$, $p = 0.757$, $E^2 = 0.011$; 2-back: $\chi^2(2) = 1.3$, $p = 0.526$, $E^2 = 0.021$). *N-back RT* was not affected by *sound condition* (F(2, 55) = 2.2, $p = 0.117$, $\eta_p^2 = 0.075$).

Other tasks did not show significant effects of *sound condition* (*ASR*: F (2, 56) = 0.5, $p = 0.631$, $\eta_p^2 = 0.016$; *VSR*: F(2, 56) = 1.3, $p = 0.286$, $\eta_p^2 = 0.044$).

4. Discussion

4.1. Analysis of results

Our study is to our knowledge the first experimental study to explore the effects of impulsive sound on a working persons' physiological and psychological stress responses and cognitive performance. Impulsive sound 65 dB L_{Aeq} was compared with two other types of sound: quiet sound 35 dB L_{Aeq} and steady-state sound 65 dB L_{Aeq}. Quiet sound presented a condition without noise load, whereas Steady-state sound presented a sound at the same sound level as Impulsive sound, but without a special character. Compared to Quiet sound, Impulsive sound was more annoying, loading, caused lack of energy, and higher cortisol levels in plasma indicating an acute stress response. In addition, Impulsive sound decreased performance accuracy in the 3-back task compared to performance during Quiet sound. Therefore compared to Quiet sound, Impulsive sound caused more psychological and physiological stress and decreased performance, which confirmed hypothesis H1. Impulsive sound differed from Quiet sound in psychological, physiological, and performance effects. However, systolic blood pressure was lower during Impulsive sound than Quiet sound, which is opposite to our expectations. Compared to Steady-state sound, Impulsive sound was considered more annoying, loading, and causing lack of energy. Thus, the subjective estimations of the impact of Impulsive sound and Steady-state sound were different, which indicates that working during

Impulsive sound was subjectively more stressful (H3). No difference in physiological and performance effects indicate small effect. The reason why exposure to Impulsive sound and Steady-state sound did not result in different physiological and performance effects is the effect of an elevated sound level (i.e., noise) as such. Already, the Steady-state sound (carrying no impulsive character) differed from Quiet sound in psychological and physiological measures. Steady-state sound caused more annoyance and raised plasma cortisol levels compared to Quiet sound, which means that already raising the sound level caused negative effects (H2). Taken together, working during Impulsive sound caused effects seen in one or several physiological, psychological, and performance measures compared to Quiet sound. Part of this stress effect was due to the increased sound level (as shown by condition Steady-state sound), but there was also an extra effect not attributable to the increased sound level as such.

Exposure to both Steady-state sound and Impulsive sound increased circulating cortisol concentrations compared to Quiet sound. This result agrees with several studies that have examined the influence of noise on a working person. A study examining steady-state noise exposure at 90 dB L_{Aeq} while working on arithmetic tasks found elevated cortisol levels after the exposure when compared with a condition with steady-state noise of 55–60 dB L_{Aeq} (Miki et al., 1998). In addition, working during intermittent two-intensity level broad-band noise 99 dB L_{Aeq} was related to a slight raise in cortisol concentration compared with exposure to 45 dB L_{Aeq} noise (Brandenberger et al., 1980). However, just working on the tasks, without the noise, increased cortisol levels compared to a baseline without tasks and noise (Brandenberger et al., 1980). The impact of the cognitive tasks is also evidenced by a study where an increase in cortisol concentrations was related to intermittent background noise at 90 dB L_{Aeq}, but only in a high-effort situation (Tafalla & Evans, 1997). Therefore, elevated cortisol concentrations might reflect the greater effort needed to perform the task during the noise exposure. Furthermore, since the cortisol responses to Steady-state sound and Impulsive sound in our study did not differ, this might indicate that the sound level plays a crucial role in triggering the cortisol response during mental work.

In general, a meta-analysis of noise effects on performance concluded that performance accuracy would be more affected by noise than speed and that SPL of noise itself may not be of central importance for performance (Szalma & Hancock, 2011). Our results are in accordance with these conclusions. Impulsive sound decreased 3-back accuracy compared to performance in Quiet sound, but reaction times were not affected. In addition, Steady-state sound and Quiet sound did not differ in performance.

The Impulsive sound had a fixed frequency of 2 Hz. The level difference was relatively small ($D_{\mathrm{L}} = 8.2$ dB) because the impulse frequency was so high (previous impulse could not decay properly while the next already begun). However, the onset rate was large (236 dB/s; see Table 2; Fig. 2). These parameters together lead to an expected penalty of $k = 7.1$ dB according to the penalty model of Nordtest (2002). This means that Steady-state sound must be played 7.1 dB louder than Impulsive sound to produce the same annoyance rating. According to Rajala and Hongisto (2020), the annoyance penalty due to impulsive sound increases with increasing D_{L}. D_{L} values up to 40 dB are usual for many impulsive sounds occurring in our daily life. It is, therefore, justified to expect that impulsive sound having larger D_{L} could lead to stronger adverse effects than our study could reveal. It is justified to study in the future how the prominence (or annoyance penalty) of impulsive sound affects people.

An unexpected result was that during exposure to Impulsive sound, systolic blood pressure was lower than during Quiet sound. A similar trend can be also seen in the noradrenaline levels in plasma, where the raw p-value between Impulsive sound and Quiet sound was under 0.05, but after Benjamini-Hochberg correction the difference was not significant and pairwise comparisons were non-significant. These two variables were expected to show similar reactions, since the catecholamine neurohormones noradrenaline and adrenaline regulate heart rate and blood pressure (McEwen, 2007). However, the possible effect was expected to be the opposite. In previous studies, even loud noise levels (90—99 dB L_{Aeq}) have not influenced circulating noradrenaline levels (Brandenberger et al., 1980; Miki et al., 1998) and noise exposure of 95 dB had no influence on systolic blood pressure, but increased diastolic blood pressure (Andrén et al., 1982). However, when study participants were performing tasks requiring high effort, 90 dB L_{Aeq} noise raised noradrenaline levels (Tafalla & Evans, 1997). In their study, the effort was manipulated by giving feedback on the task performance. Our tasks without feedback might have more variation in the effort that participants put in them. Therefore, no difference in noradrenaline levels or in systolic blood pressure would be in accordance with most previous studies.

Steady-state noise exposure at sound levels between 50–80 dB L_{Aeq} was correlated with changes in the LF/HF ratio of HRV (Lee et al., 2010). The *sound conditions* in our study did not differ in this same measure of HRV, which might be due to lower sound levels in our study or the fact that their study was a within-subject cross-over study and our was a parallel-group study. A third difference is that our sound exposure was presented during mental work. Therefore, already Quiet sound involved elements causing stress since there were tasks to be performed.

4.2. *Strengths and limitations*

Strengths of our study included well-controlled *sound conditions* and the fact that the different effects of sound exposure were widely measured, considering psychological, physiological, and performance effects. Furthermore, we used conservative Benjamini-Hochberg procedure for false discovery rate for the main effects and Bonferroni correction for multiple comparisons to make sure that any differences reported are robust. Even though, our sample size enabled us to detect reliably only large effects, our study shows that large differences exists between these sound conditions in psychological, physiological, and performance responses. This enabled us to examine the hypothesis that were based on the resource-based models of performance under stress and not on effect sizes per se.

The *sound conditions* were designed to explore the effects of basic sound characteristics, i.e., sound level and impulsiveness. However, the results could have been different with the selection of different kind of impulsive sound. Furthermore, in our study the participants had practiced the tasks well before the sound exposure, since both practice and the baseline phase were presented before the test phase. Practicing the tasks might diminish the variability of performance making it more stable, since more variability was seen in performance in the baseline phase. Due to this variability, it is important that all participants practiced the task the same amount before the sound exposure. The shorter exposures and new tasks might show different results. In addition, the acute effects observed in our experiment cannot be directly translated to any long-term effects, which determine the ultimate health effects of environmental noise exposure. Therefore, studies on long-term noise exposure are needed where the noise exposure is carefully controlled.

5. Conclusions

We investigated the effects caused by exposure to impulsive sound (65 dB) on a person working with tasks needing constant concentration. We compared impulsive sound to two reference *sound conditions*, which were quiet sound (35 dB) and steady-state sound (65 dB). Impulsive sound differed from Quiet sound in its effects on psychological and physiological measures and performance. Psychological measures separated the effects related to impulsive sound and steady-state sound. Already, exposure to steady-state sound increased circulating cortisol concentrations compared to quiet sound, i.e., caused an acute physiological stress effect. Therefore, for impulsive sound, some of the observed effects may be related to the sound level as such, but a small extra effect of the special sound characteristic of impulsivity was also present. The present results indicate that impulsive sound might generate stronger annoyance if a person is working during the sound exposure compared to just hearing the sound. Exposure to impulsive sound causes psychological and physiological load and decreases performance. Therefore, environmental noise control ought to pay extra attention to impulsive noise, especially in settings where cognitive work is required.

CRediT authorship contribution statement

Jenni Radun: Methodology, Software, Investigation, Formal analysis, Visualization, Writing – original draft. **Henna Maula:** Methodology, Investigation, Formal analysis, Writing – review & editing. **Ville Rajala:** Resources, Software, Investigation, Writing – review & editing. **Mika Scheinin:** Supervision, Methodology, Formal analysis, Resources, Writing – review & editing. **Valtteri Hongisto:** Conceptualization, Methodology, Resources, Supervision, Project administration, Funding acquisition, Writing – original draft.

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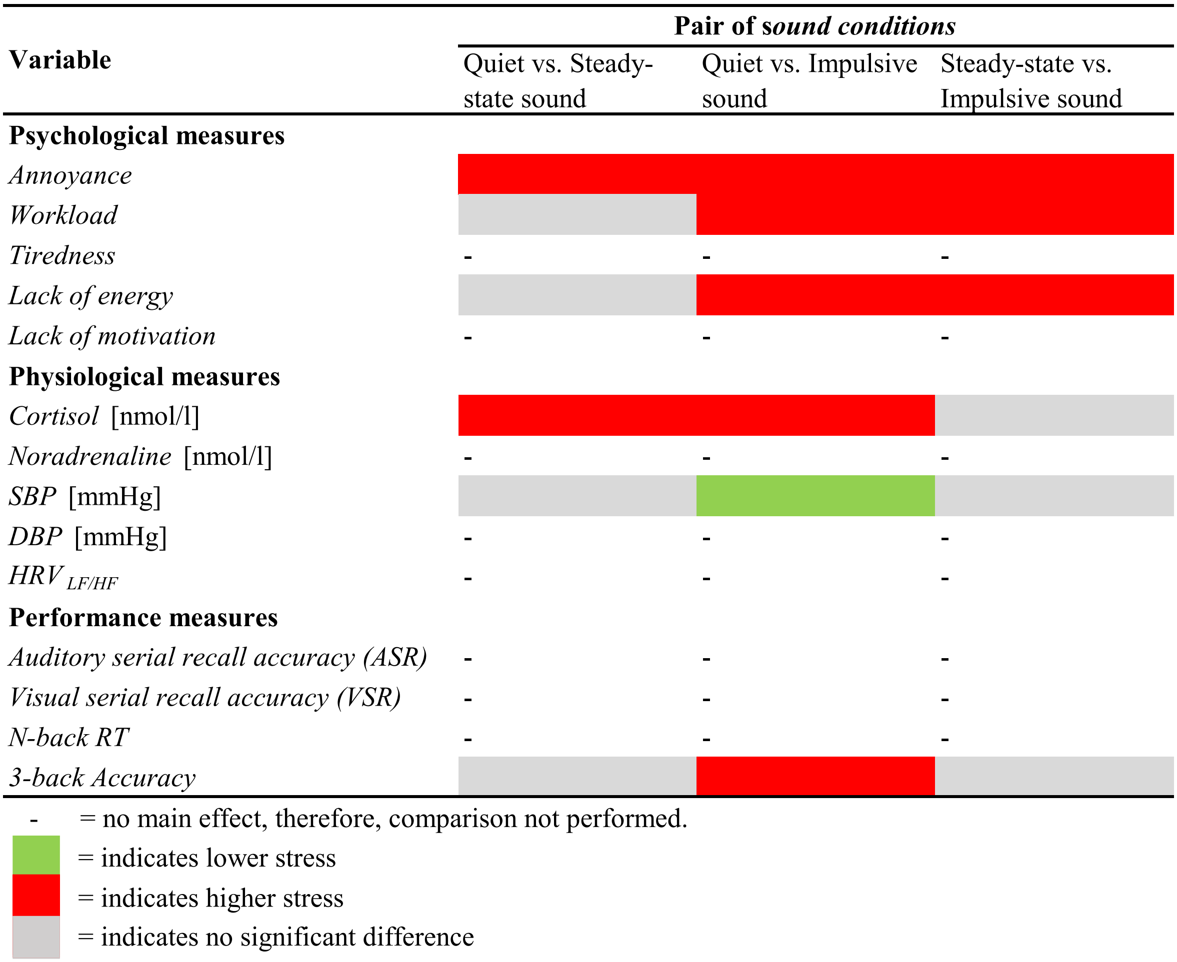
Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2022.101819.

Appendix



Variable	Pair of *sound conditions*		
	Quiet vs. Steady-state sound	Quiet vs. Impulsive sound	Steady-state vs. Impulsive sound
Psychological measures			
Annoyance	🟥	🟥	🟥
Workload	⬜	🟥	🟥
Tiredness	-	-	-
Lack of energy	⬜	🟥	🟥
Lack of motivation	-	-	-
Physiological measures			
Cortisol [nmol/l]	🟥	🟥	⬜
Noradrenaline [nmol/l]	-	-	-
SBP [mmHg]	⬜	🟩	⬜
DBP [mmHg]	-	-	-
$HRV_{LF/HF}$	-	-	-
Performance measures			
Auditory serial recall accuracy (ASR)	-	-	-
Visual serial recall accuracy (VSR)	-	-	-
N-back RT	-	-	-
3-back Accuracy	⬜	🟥	⬜

- = no main effect, therefore, comparison not performed.
🟩 = indicates lower stress
🟥 = indicates higher stress
⬜ = indicates no significant difference

Fig. A.1. The main results of the experiment. The pairwise comparisons' statistically significant effects and their directions are presented.

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