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Distinct Influence Of Everyday Noise On Cardiovascular Stress

Jeppe H. Christensen[1]
Eriksholm Research Centre
Snekkersten, Denmark

Klaudia E. Andersson
Eriksholm Research Centre
Snekkersten, Denmark
Institute of Clinical Research
University of Southern Denmark, Odense
Research Unit for Oto-Rhino-Laryngology,
Odense University Hospital, Denmark

Tobias Neher
Institute of Clinical Research, University of Southern Denmark, Odense
Research Unit for Oto-Rhino-Laryngology, Odense University Hospital, Denmark

ABSTRACT

High-intense environmental noise is detrimental to cardiovascular health. However, individual differences have not been considered, and reported effects cannot be generalized to noise levels reflecting everyday life.

Here we explore the relationship between daily-life sound exposure and heart rate with longitudinal data from young normal hearing individuals. Specifically, we analyze the daily short-term covariation between changes in heart rate and sound intensity using multi-level regression and Granger analysis.

We find strong evidence that everyday sound exposure is related to heart rate in all participants. Sound intensity is linearly and positively related to heart rate while the ambient signal-to-noise ratio has a negative association to heart rate in louder environments. Across participants we establish that the causal influence has a distinct temporal pattern with stronger influence of the sound environment, especially sound intensity, on heart rate from 10:00 to 15:00 than for the rest of the day.

We propose that sound sensitivity measures represent a combination of the amount of effort asserted to listen under noisy conditions during the active periods of a day and the direct physiological sound-induced stress reaction. The methodology can increase our understanding of human ecophysiology of hearing, and of the physiological effects of everyday noise.

[1] jych@eriksholm.com

1. INTRODUCTION

It has recently been suggested that human heart rate (HR) and cardiovascular stress is a function of short-term changes in the sound intensity of the ambient acoustic environment. For example, El Aarbaoui & Chaix (2019) documented a positive and significant association between everyday HR and ambient sound pressure level (SPL) in 75 individuals across 7 days of recording (El Aarbaoui & Chaix, 2019). The study also found a negative association between SPL and the heart rate variability, which suggest that effects are related to stress (Kim et al., 2018), while a modulating effect of environment (home vs. public space vs. transport) suggests that effects are larger in typically noisy places. Along the same lines, Christensen et. al., (2021) documented a positive association between 5-minute mean HR and ambient sound intensity in a group of hearing aid users across 3 months of normal life. The effect sizes of the two studies are highly comparable (0.141% per dB SPL and 0.154% per dB SPL, respectively), pointing towards a basic physiological mechanism. In addition, the latter study also considered other features of the acoustic environment and found a negative association between mean HR and the ambient signal-to-noise ratio (SNR) – and this effect was largest in louder environments with intensities above the overall observed median of 60 dB SPL. Thus, while high ambient sound intensity (SPL) increase HR, the sound clarity (SNR) reduces HR especially in louder environments. This suggests that noise should not be characterized just by its intensity alone but also by acoustic features related to e.g., speech understanding, which are known to modulate cognitive effort especially for individuals with a hearing loss (Pichora-Fuller et al., 2016). While the direction of cause is implied (ambient sound affecting HR), there is also evidence to support this. In a laboratory study, Shoushtarian et. al., (2019) demonstrated that mean heart rate increases immediately following the onset of acoustic noise as compared to in complete quiet (Shoushtarian et al., 2019). In addition, the magnitude of increase in HR was directly associated with the intensity of the noise. These findings indicate that there is a direct and short-term causal influence of noise exposure on cardiovascular regulation. Still, it is unknown if direction of causality can also be established in real-world data since behavior is not controlled for. For example, if individuals are often performing stress-full activities while being exposed to loud noise, a reverse or non-existing direction of cause might be implied. On the other hand, individuals experiencing stress might seek out less noisy environments to relax and, in such cases, increased SNR would lead to decreased HR in a bidirectional or reverse coupling. Thus, establishing the direction of cause over time might be helpful for teasing apart the distinct impact of everyday ambient noise on human cardiovascular stress.

In this paper, we explore the short-term associations between HR and features of the acoustic environments from real-world data recorded from 9 normal-hearing individuals over 3 weeks. The direction of cause over time is assessed with Granger causality. We hypothesize that the two features of everyday sound (SPL and SNR) distinctly moderate HR, and that the Granger causality analysis shows evidence for a direct impact from ambient sound on HR, which varies in strengths as a function of time-of-day due to daily life activities. Data is recorded continuously and unobtrusively by commercially available wristbands and hearing aids.

2. METHODS

2.1. Participants and equipment

Test participants consisted of nine younger (22 to 31 years of age, M = 25.8 years of age) individuals studying at the University of Southern Denmark, Odense, Denmark. HR were measured by Garmin vivosmart™ 4 wristbands and sound data were recorded by Oticon Opn S™ hearing aids worn on top of clothes using custom-made clips. Both HR and sound data were continuously transferred (via Bluetooth) and stored with associated timestamps on iPhones carried by the participants. The participants each completed a 3 week field trial (21 days) of data logging.

2.2. Data and pre-processing

The data consist of time-series of instantaneous ambient SPL and SNR, and HR. SPL and SNR were logged every 20 seconds while HR were logged for each detected heartbeat. To align sampling

time, HR were post-hoc averaged around each sample of SPL and SNR in the time-widow [-5; +5] seconds.

To eliminate potential confounds from excessive physical activity, data with HR above the 5% percentile was removed from each participant. In addition, prior to modeling, SPL and SNR were binned into participant-specific percentiles 10% wide and HR data were normalized by subtracting the mean across all samples for each participant. This way, relative changes in HR in relation to relative changes in sound exposure is investigated. Lastly, each sound data sample was associated with an activity score estimated by the Apple Health app in the iPhones on the form "running", "walking", "stationary", or "biking". In addition, to avoid confounds from sparsely sampled data occurring very late or very early in time we only included data recorded between 6:00 and 22:00.

2.3. Statistical Analysis

Associations between sound data and HR were modelled with a linear mixed-model including random intercepts for participant ID and hour-of-day. In addition, autocorrelation among the HR samples were controlled for by adding an auto-regressive term on the order of 1. Finally, as a sanity check, the activity score was included as a random co-regressor in a separate model to identify the impact of physical activity on the associations.

Granger causality tests if future values of a time-series can be better predicted by a combination of past values of itself and another time-series than by its past values alone. The statistical test is based on a Wald test of the differences in explained variance between two predictive models; one that only contain past values up to a selected lag, and one that also include past values of another time series. Direction of causality between two timeseries X and Y is then inferred from testing the two hypotheses: H_0^1: X granger cause Y, or H_0^2: Y granger cause X. If both H_0^1 and H_0^2 is accepted, then there exists no linear causal relationship between X and Y. If H_0^1 is accepted but H_0^2 is rejected, then there exists a linear causality running unidirectionally from Y to X. If H_0^1 is rejected but H_0^1 is accepted, then there exists a linear causality running unidirectionally from X to Y. Finally, if both H_0^1 and H_0^2 are rejected, then there is mutual Granger causality between X and Y indicating either a feedback relationship or that changes in X and Y are driven by a common latent variable. The method has previously been successful in investigating cardiovascular effects (Ghouali et al., 2016; Porta et al., 2013). In case of mutual causality, the assessment of the dominant causality can be based on a direct comparison between *F* values assessed over opposite causal directions (Paluš & Stefanovska, 2003). Accordingly, the directionality index (DI) is defined as

$$DI_{X\to Y} = F_{X\to Y} - F_{Y\to X}, \quad (1)$$

where $F_{X\to Y}$ and $F_{Y\to X}$ represent the F values assessed from X to Y and vice versa, respectively. $DI_{X\to Y} > 0$ indicates that the causal direction from X to Y is prevalent over the reverse one, while $DI_{Y\to X} < 0$ points out the opposite situation. $DI_{X\to Y}$ is exclusively capable of identifying the dominant causality: indeed, values larger or smaller than zero does not exclude bidirectional interactions. In addition, DI close to 0 might indicate: (i) a full uncoupling between X and Y; (ii) closed-loop interactions between X and Y with none of the causal directions taking real pre-eminence; and (iii) synchronization between X and Y.

Granger causality tests were performed on SPL, SNR, and HR timeseries for each day, participant, and 3-hour time-windows with 1-hour overlaps. We report both the proportion of tests favoring each possible test outcomes as well as the average improvement in model prediction ($DI_{X\to Y}$). All statistical analysis and visualizations were done in R v. 3.6.1.

3. RESULTS

On average, the nine participants logged sound and HR data for 7.62 hours per day (SD = 6.6 hours) across the 21 days of the field trial. The ditribution of the total amount of logs per hour is shown in Figure 1 together with the cut-off points for excluding data either logged very early or very late (red dashed lines).

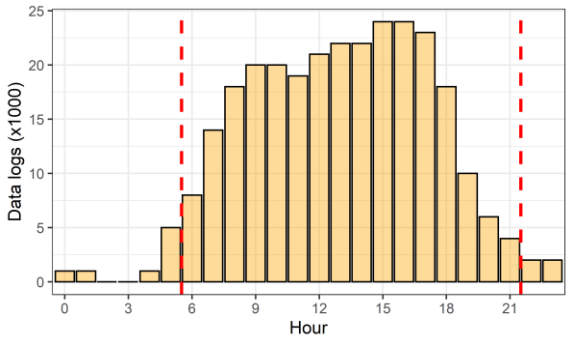

Figure 1: Distribution of data logs pooled from all participants. Data between the two red dashed lines are used for subsequent modeling. Note, one data log corresponds to 20 seconds of wear time.

3.1. Association between HR and SPL, SNR

HR significantly associated to both SPL and SNR (likelihood ratio tests against NULL model: $\chi^2(38) = 4623$, $p < 0.001$), confirming previous results (Christensen et al., 2021; El Aarbaoui & Chaix, 2019), and documenting a strikingly linear relationship from lowest to highest percentile SPL and SNR (see Figure 2b).

Figure 2a shows the grand mean relative HR against the observed percentiles of SNR and SPL, suggesting that in louder environments higher SNR leads to lower mean HR. Figure 2b shows the estimated coefficients from the LME modeling of HR with SPL and SNR percentiles as predictors. The full model (fixed and random effects) explained 45.7% of the total variance in HR while the fixed effects alone contributed with 9.8%. This latter number is approximately twice as high as previously reported (Christensen et al., 2021). However, adding the iPhone-classified activity estimate as a random intercept grouping increased the models account of the total explained variance to 56.9% and decreased the contribution of the fixed effects to 4.23%, which is comparable to previously reported effect sizes. However, the addition of the activity regressor did not change the coefficients for SPL and SNR (Figure 2b) notably.

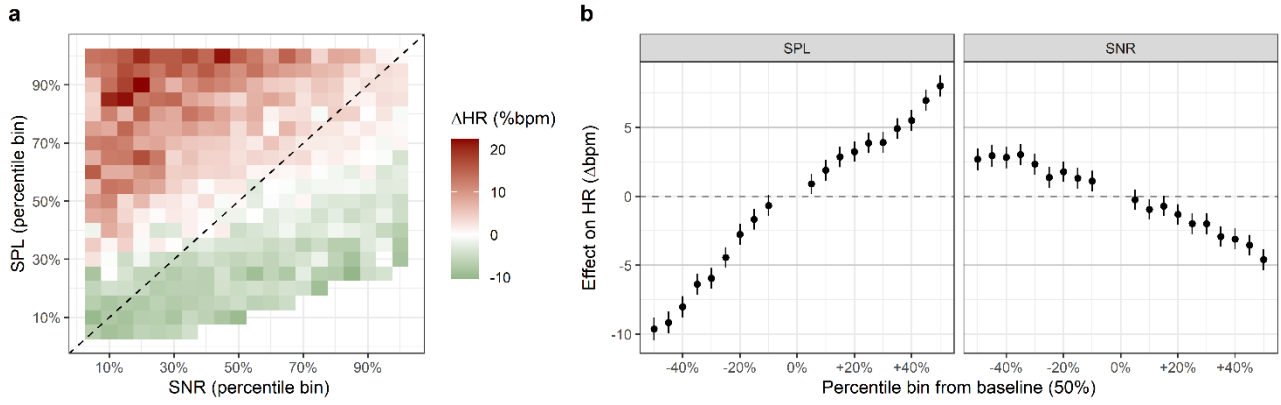

Figure 2: The grand mean relative HR separated by percentiles of the ambient SNR and SPL (a) and the LME model coefficients (b). Note that the coefficients in (b) are relative to the baseline condition (50%) and that error bars indicate the 95% confidence intervals.

3.2. Direction of cause between HR and the ambient sound environment

Granger causality was estimated on a total of 1474 unique time-series (days, participants, time-windows). First, we assessed the overall proportion of time-series favoring the different types of Granger causality across the 21 days of recording. Thus, for each hour 7:00 to 21:00, the proportion of days providing no evidence or evidence to a bi-directional, direct, or reverse, direction of granger causality was assessed. As shown in Figure 3a, SPL and SNR are more likely to directly impact HR than a reverse or bi-directional relation.

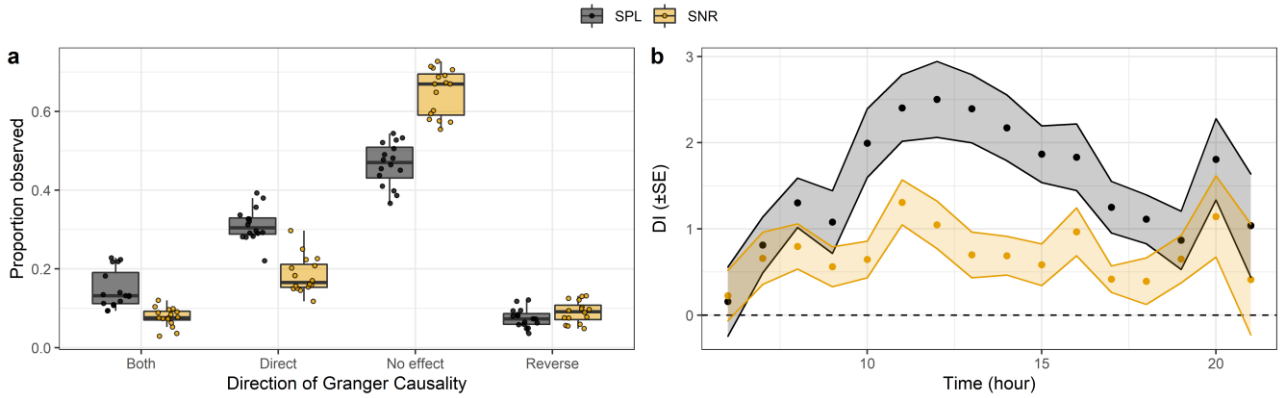

Figure 3: Proportion of time-series providing evidence towards the four different directions of Granger causality (a) and the temporal dependency of the Directionality Index (*DI*) across all days.

In addition, SPL are overall more likely to impact HR than SNR (higher proportion of direct effects). We can inspect the improvement in model prediction of HR when adding either SPL or SNR (i.e. $DI_{SPL\ or\ SNR \rightarrow HR}$) by computing the mean *DI* across days and separated by time (Figure 3b). Evidently from Figure 3b, the biggest impact of SPL on HR is from 10:00 to 15:00, while the impact of SNR is distributed more evenly throughout the day.

4. CONCLUSIONS

Using longitudinal data of daily life exposure to different sound environments and instantaneous HR, we document that HR in normal hearing younger individuals are positively associated with real-world SPL and negatively associated with real-world SNR. This finding replicates previous studies (Christensen et al., 2021; El Aarbaoui & Chaix, 2019) while the granger Causality of the direction of cause corroborates previous laboratory studies (Shoushtarian et al., 2019) and point toward a basic physiological mechanism of the impact of everyday noise on cardiovascular control.

The influence of signal-to-noise ratio on real-world HR has not previously been recognized in the noise impact literature, and we speculate that effects arising from changes in ambient SNR are related to listening activities – i.e., noisy environments are harder to listen in and therefore potentially cause a stress reaction.

The temporal dynamic of the Granger causality (Figure 3b) suggests that sound-induced stress from changes in SPL are more prominent during typical active hours of the day (10:00 to 15:00) while the impact of changes in SNR on HR are non-localized in time. This might be due to the fact that modulation of HR with ambient SNR are expected to occur for specific listening situations involving cognitive processing of target sounds through noise and taking place throughout the day.

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