More is less – Positive effects of higher volume ventilation sound on cognitive performance and acoustic comfort in offices

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ABSTRACT

Sound emissions of ventilation units are mostly referred to as noise and are subject to a minimization policy. Silencing causes technical effort and sometimes even higher energy consumption. Additionally, this study reveals that silencing may be counterproductive in open-plan offices, since employees may even benefit from higher volume ventilation sound. This positive effect occurs when disturbing background speech is masked by ventilation sound. In this study acoustics of an open-plan office at one receiver positon incorporating background speech were auralized. Then ventilation sounds of two different decentralized ventilation units at three ventilation rates producing sound emissions in between 25 and 45 dB(A) were added. Participants were exposed to these sound scenarios during a laboratory experiment. Results reveal that participants performed better at a working memory task during presentation of one of the high volume ventilation sounds and acoustic comfort and privacy were judged to be better as well. However, sound quality of ventilation sounds needs to be investigated and purposefully adapted since different effects were found for the two ventilation units, although the overall A-weighted sound pressure levels were comparable.

Keywords: noise, open-plan office, sound masking I-INCE Classification of Subjects Number(s): 51.6, 51.7, 63.2, 63.5

1. INTRODUCTION

The demand for the lowest possible noise level in offices is unquestionable. Under the premise that ventilation units are undesirable noise sources, low target values were defined:

- DIN 4109: $L_{AF,\,max}$ = 30 dB
- DIN 18041: $L_{NA,\,building}$ = 30 dB, 35dB or 40 dB depending on the requirements (high, medium or minimum) specified for the room use
- DIN EN ISO 11690 1: L_{pAeq} = 30 to 40 dB (single office); L_{pAeq} = 35 to 45 (open-plan office)
- VDI 2569 $L_{AF,\,max}$ = 35 dB to 40 dB of continuous noise from ventilation systems without noticeable individual tones in single offices; $L_{AF,\,max}$ = 40 dB to 45 dB in open-plan offices if masking of information-containing noise (e.g. speech) is desired

However, there are few validated studies on the origins of those target values. The technically feasible noise level of ventilation units is lower today than in the past because quieter fans and improved silencers can be used. However, the requirements defined in standards are often more rigorous and cause - at constant ventilation rates - both technical effort and sometimes even higher energy consumption due to pressure losses. Both aspects are cost-effective and influence the application of mechanical ventilation units. The acoustic strain in offices has recently been investigated intensively. Several studies (1, 2) led to two key findings:

First, in the opinion of the employees noise is at the forefront with regard to sources of annoyance in open-plan offices. Secondly, the omnipresent background speech - whether loud or soft – dominates perception of noise, while technical sound sources are less relevant.

These findings have already been introduced into standards (e.g. ISO 3382-3). Against this background, artificially generated masking sounds were investigated (3) in order to superimpose background speech. So far, sound masking systems are common in the US and mostly broadband noise

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similar to ventilation sound is used (4). The sound masking effect of these sounds is limited but the annoyance caused by the broadband noise itself is considered appropriate. It is therefore to be questioned whether the sound emissions from ventilation units are to be regarded as noise and should be subject to a minimization policy with a static target value.

Sound levels of other noise sources in offices, meeting rooms and classrooms vary depending on the room use and performed activities. Background speech caused by communication of colleagues may temporarily reach levels which by far exceed the ventilation sound even at high ventilation rates. In other periods background sound levels fall below the level of ventilation sound. A static target value, independent of the sound caused by varying activities and room uses therefore does not seem appropriate. Additionally investigations (4) have shown that in open-plan offices ventilation sounds may not in principle be regarded as noise sources but depending on the usage scenario they may be regarded as wanted sound since they are superimposing unwanted background speech.

The reported research project seeks for a paradigm shift in the consideration of sound emissions from ventilation units but also other office equipment which should not only be considered as potential noise sources but as a means for targeted conditioning of room acoustics. The ventilation unit may therefore become a part of the integral room conditioning (climate and acoustics) and the target values may be adaptively adjusted in consideration of the needs of the employees and their current activities.

2. METHOD

The effects of the sound emissions of two typical decentralized ventilation units on acoustic comfort and performance were investigated by means of a laboratory listening test in a simulated office environment.

2.1 Selection of sounds

From SIEGENIA-AUBI KG two typical ventilation units (AEROMAT VT WRG 1000; AEROVITAL) were provided, which can be operated at different air exchange rates and thereby produce different sound emissions.

2.2 Recordings

The recordings were made in a door test stand at the Fraunhofer IBP using an artificial head and measurement microphone. The ventilation units were mounted on a wooden auxiliary construction and positioned in the doorway. The reverberation time in the test stand was adjusted to 0.8 seconds which is typical for office environments. The recordings were made both at 1 meter and 2 meters distance and for different air exchange rates. For the listening test the recordings at 2 meters distance were chosen. Recordings comprised different air exchange rates (AEROMAT VT WRG 1000: Level 1, 2 and 3; AEROVITAL: Level 2, 4 and 10) covering a suitable span of sound pressure levels (ca. 25 dB(A) to 45 dB(A)) for the listening test. During the listening test combinations of ventilation sound and background speech and the ventilation sounds themselves were presented. The octave band levels of the test signals are shown in Table 1.

Table 1 – Octave band levels [dB(A)] of the test signals (S = speech; L1 = AEROMAT VT WRG 1000; L2 = AEROVITAL; S1-S10 = settings of air exchange rates)

Signal	Frequency [Hz]							
	125	250	500	1000	2000	4000	8000	∑
Silence	-	-	-	-	-	-	-	
L1S1	17,57	16,70	19,25	18,63	11,54	4,58	8,46	24.55
L1S3	28,46	32,96	37,00	36,85	28,29	18,02	9,21	41.23
L2S4	14,83	24,02	26,45	22,38	14,02	2,29	8,35	29.69
L2S10	18,64	34,65	35,94	34,54	26,90	17,31	9,13	40.14
S	6,63	27,03	33,57	29,08	21,37	17,26	12,39	35.80
SL1S1	17,90	27,41	33,76	29,64	21,95	17,51	13,81	36.18

SL1S2	21,22	29,59	34,82	31,68	23,83	17,93	13,75	37.69
SL1S3	28,37	33,90	38,51	37,45	29,12	20,71	14,17	42.24
SL2S4	15,36	28,63	34,31	29,99	22,37	17,60	13,84	36.73
SL2S7	14,62	31,40	35,57	31,99	23,86	17,79	13,56	38.40
SL2S10	18,88	35,29	37,86	35,62	27,97	20,31	14,17	41.45

2.3 Office auralization

Given the limited project resources not all imaginable office sound scenarios can be reconsidered. An almost unlimited number of variations can be thought of depending on the specific spatial conditions (floor plan), room acoustic design and occupation of the office. In order to simulate a representative acoustic office environment an auralization according to the examples given in the new draft of the VDI 2569: 2016-02 was prepared using the room acoustic planning software ODEON. Since most offices in reality match room acoustics class C of this directive, the auralization was also based on this quality. Figure 1 depicts a visualization of the open-plan office. The resulting room acoustic characteristics at the receiver position are shown in Table 2.

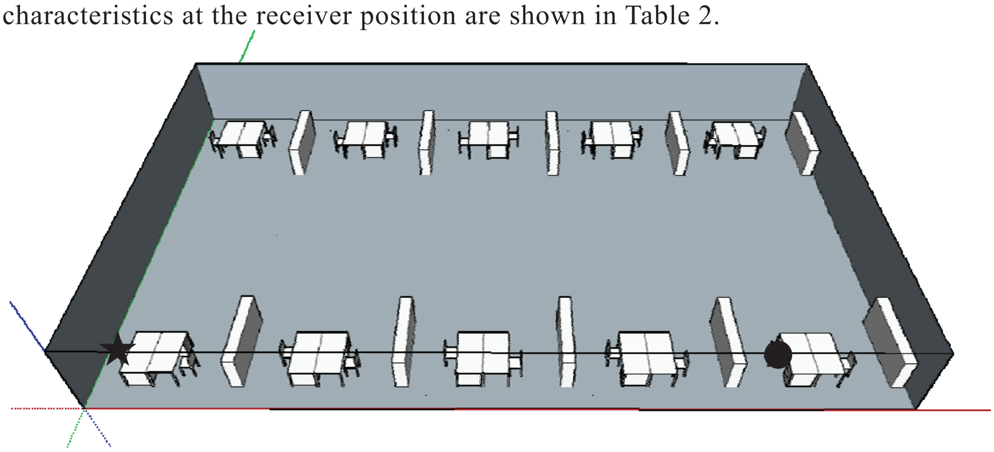

Figure 1 –Visualization of the auralized office scenario. The receiver position is marked in the figure by a dot. The transmitter position is illustrated by a star.

Table 2 – Room acoustic properties at the receiver position

Parameter	Value
T30 [s] (1000 Hz)	0.69
SPL(A) [dB]	35.2
Position [m]	21
$D_{2,s}$ [dB]	5.67
$L_{p,A,S,4m}$ [dB]	48.74

For the listening test a single speaker at a constant position was simulated as noise source. This represents the worst possible case. Auralization of several speakers at different positions has been omitted since their interference potential is currently still the subject of scientific discussion (5). It is argued that in the case of simultaneous speaking of more than one person voices might superimpose each other so much that the individual interference potential is reduced. However, at present the studies on this assumption are based on rather unrealistic assumptions with a very large number of simultaneous speakers. Additionally, it has to be assumed that a speaker at a directly neighboring workstation cannot be masked by a conventional ventilation sound since the speech level at 1 meter distance is about 60 dB (A). Therefore a receiver position at a distance of 21 meters has been selected for auralization, so that the possibility of a masking effect is given.

2.4 Listening test

The listening test followed a one-factorial experimental design with 12 levels (sound condition: Silence, Speech, L1S1, L1S3, L2S4, L2S10, SL1S1, SL1S2, SL1S3, SL2S4, SL2S7, SL2S10) and repeated measurements (within-subjects design).

In total n = 29 subjects (11 female; 18 male) took part in the listening test. The subjects were between 20 to 66 years old (M = 25.6 years, MD = 25 years). A small allowance was paid for participation.

The listening test was performed at a test facility of the Fraunhofer Institute for Building Physics in Stuttgart. The experiment was programmed using the software PsyScope X (version B57) and presented on iMac computers (display size 21" with a resolution of 1920 x 1080 px) with the Mac OSX operating system (Yosemite). The sounds were played using Sennheiser HD600 headphones. The acoustic scenarios in the laboratory were calibrated using an artificial ear (GRAS 43AA-S2 CCP Ear Simulator Kit), a microphone preamplifier Type 26AC (GRAS Sound & Vibration) and a sound analyzer Type 110 (Norsonic Tippkemper GmbH).

In each experimental session four subjects were tested in parallel in the same room. Each workstation was separated by translucent partitions between the tables. A serial recall task was used for the performance test, where subjects had to memorize and recall (after a memorization interval of 8 seconds) a sequence of the numbers from 1 to 9 in the exact order of presentation. The numbers were presented on the screen in random order. Recall was carried out by clicking on numbers on the screen.

This task was processed by the subjects during 12 different experimental conditions (Silence, Speech, L1S1, L1S3, L2S4, L2S10, SL1S1, SL1S2, SL1S3, SL2S4, SL2S7, SL2S10). The subjects were given both an oral and a written instruction. They were not informed that the experimental sounds were produced by ventilation units. Subjects started with 8 practice trials of the task and then performed 12 trials per experimental condition. The different sound scenarios were played in random order. At the end of each test condition the subjects were asked to conduct a subjective rating of the recent sound scenario by means of online questionnaires which were setup using Limesurvey (version 2.06+). The total duration of the listening test was between 90 and 120 minutes.

The questions that were asked to judge the different acoustic scenarios were mostly the same for all experimental conditions. They differed only with regard to the wording which was adjusted to the specific experimental condition.

The subjects should evaluate annoyance of each acoustic scenario on a 5-point scale. For the evaluation of subjective annoyance the verbal rating scale defined in ISO/TS 15666 (extremely/very/moderately/slightly/not at all) was used. Since the test procedure only covers short-term presentation of the test signals it was also asked for the assumed annoyance during prolonged exposure times. Again the rating scales of ISO/TS 15666 were applied.

For experimental conditions during which a mix of speech and ventilation sound was presented, annoyance of the ventilation sound and speech were evaluated separately. Additionally subjects were asked to rate their ability to concentrate during the presentation of the sound scenarios on a 5-point scale (extremely/very/moderately/slightly/not at all). Perceived privacy was also covered by a question regarding the estimated distance (in meters) to the speaker. Subjective performance was measured by a question where subjects should evaluate their performance during the serial recall task by means of an estimated percentage of correctly reproduced numbers. In the end of the experiment some general questions were asked. Among other things, the subjects were asked whether they think that the presence of the ventilation sounds would help them to work more effectively.

3. Results

3.1 Performance test

A one-way ANOVA (repeated measures) revealed a significant main effect of the factor sound condition on the error rate ($F(11, 308) = 9.89$, $p < .001$, $\eta^2 = .261$). The comparison of the error rate of the Silence with (unmasked) Speech by a t-test showed a significant difference ($t(28) = -4.90$, $p < .001$). On average, the error rate during (unmasked) Speech is 10% higher than during Silence. Furthermore, a significant difference between (unmasked) Speech and SL2S10 (speech masked by AEROVITAL at level 10) was found in the t-test ($t(28) = 2.19$, $p = 0.037$). This significant effect was reflected by a lower error rate in condition SL2S10 in comparison to (unmasked) Speech. None of the other masked speech conditions revealed a significant t-test in comparison to (unmasked) Speech. All masked speech conditions revealed a deterioration of performance compared to Silence. In contrast, no significant differences were found for comparisons between Silence and the conditions in which pure (without speaker) ventilation sounds were presented. The pure ventilation sounds do not impair performance.

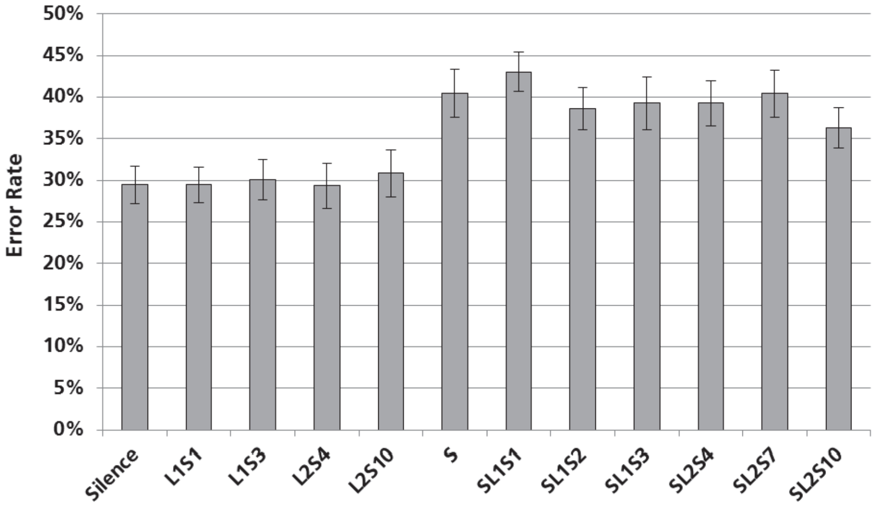

Figure 2 – The figure depicts averaged error rates (serial recall task) during the 12 experimental conditions.

3.2 Questionnaire ratings

3.2.1 Annoyance

Comparisons of the annoyance caused by the speaker during the different sound scenarios could not be calculated by means of a one-factorial ANOVA (repeated measures) since the data was not normally distributed. T-tests (which are assumed to be robust) revealed significant differences. For both ventilation units the speaker being masked by the ventilation sound at medium or high level, is perceived less annoying as compared to the unmasked Speech ($p < .05$) There was no significant difference between corresponding settings of the two ventilation units.

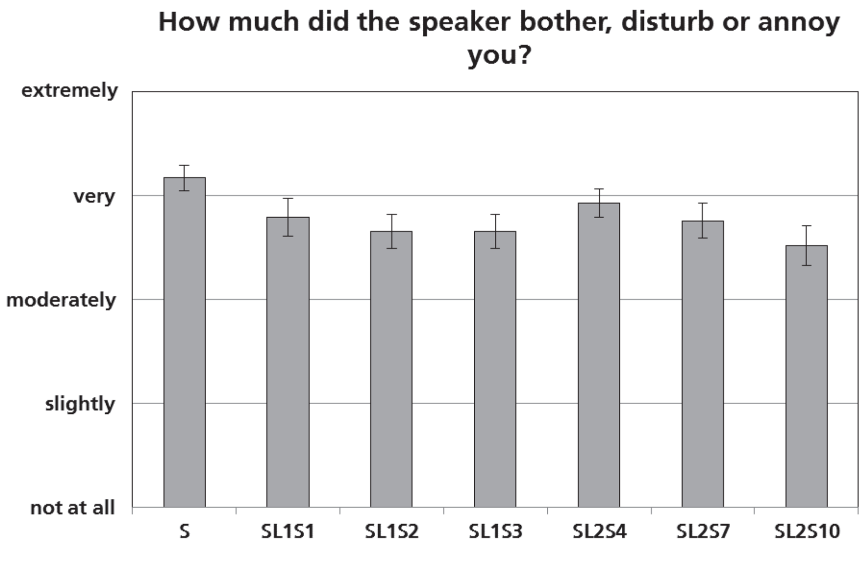

Figure 3 – The figure shows the perceived annoyance caused by the speaker during the different experimental conditions.

Comparing the annoyance caused by the ventilation sound during the different sound conditions by means of a one-way ANOVA (repeated measures) showed a significant main effect of the factor sound condition on the dependent variable annoyance ($F (10, 270) = 6:48$, $p < .000$, $\eta^2 =. 194$).

Silence is significantly less annoying than the conditions during which the pure ventilation sound or a combination of ventilation sound and the speaker was played back.

In combination with the speaker there exists also a significant difference between the annoyance ratings of the two different ventilation units each at highest ventilation level. In this case the ventilation sound of the second ventilation unit at the highest ventilation level (SL2S10) was judged to be more annoying than the ventilation sound of the first (SL1S3) ventilation unit at the highest ventilation level (t (28) = -2.22, p = .035). This difference does not exist if the two ventilation sounds are not combined with a speaker (L1S3 and L2S10: t (28) = 0.66, p = .515).

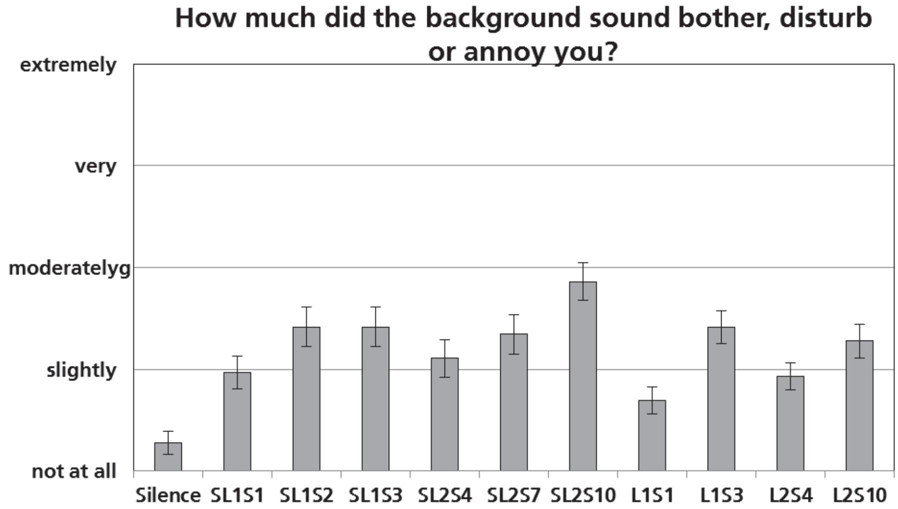

Figure 4 – The figure shows the perceived annoyance caused by ventilation sounds during the different experimental conditions.

3.2.2 Concentrativeness

The comparison of the perceived concentrativeness during the different experimental conditions by a one-way ANOVA (repeated measures) revealed a significant main effect of the factor sound condition on the dependent variable concentrativeness (F (11, 297) = 17:48 p <.000, η^2 =, 393). T-tests revealed a significant difference with regard to the evaluation of concentrativeness during silence compared to speech (t (28) = -6.41, p <. 000). The ability to concentrate during all pure ventilation sounds was rated equal to silence. Concentrativeness was not rated better during the speech sound masked by ventilation sound as compared to (unmasked) Speech.

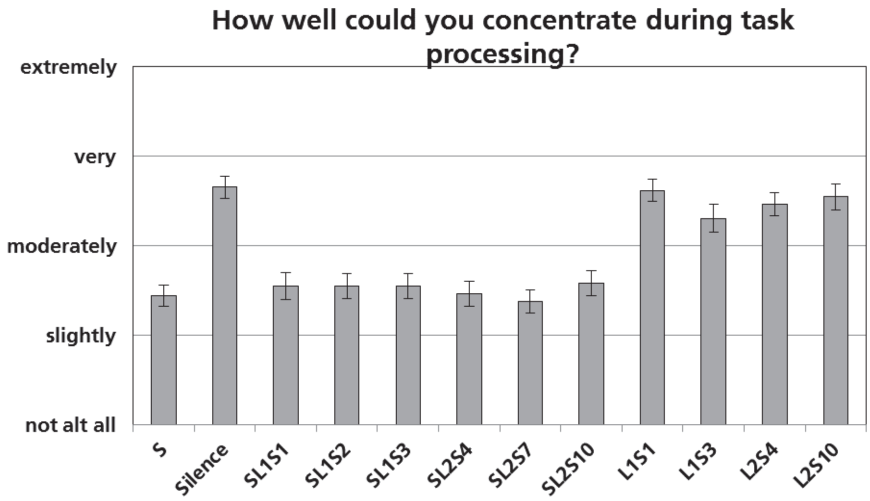

Figure 5 – The figure shows the perceived concentrativeness during the different experimental conditions.

3.2.3 Privacy

The comparison of the perceived distance to the speaker during the different experimental conditions by a one-way ANOVA (repeated measures) revealed a significant main effect of the factor sound condition on the dependent variable distance to the speaker ($F(6,138) = 2.18$, $p = .049$, $\eta^2 = .086$). The ventilation sound of AEROVITAL (L2) at medium (S7) and highest (S10) ventilation level causes the speaker to be perceived further away compared to (unmasked) Speech (SL2S7: $t(28) = -2.12$, $p = .043$; SL2S10: ($t(27) = -2.92$, $p = .007$). The mean distance during SL2S10 is 7.0 m, compared to only 4.2 m during (unmasked) Speech. However, all judgments underestimate the real distance by far.

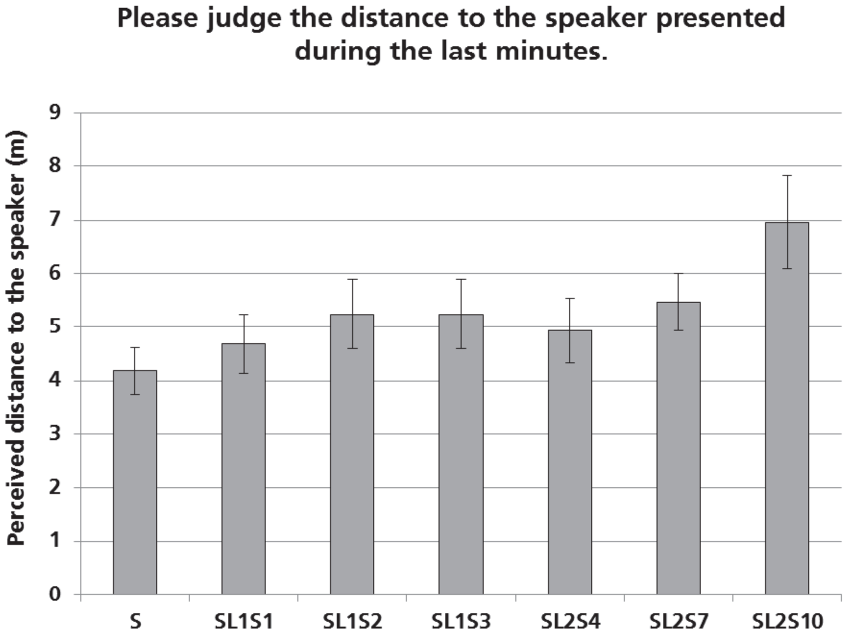

Figure 6 – The figure shows the perceived distance to the speaker during the different experimental conditions.

3.2.4 Long-term annoyance

The comparison of the expected annoyance under prolonged exposure time during the test conditions by a one-way ANOVA (repeated measures) showed a significant main effect of the factor sound condition on the dependent variable long-term annoyance ($F(11.297) = 35.36$, $p < .000$, $\eta^2 = .567$). However, the expected long-term annoyance caused by the masked speech sounds is not significantly different from that of the unmasked speaker. At low ventilation rates the expected long-term annoyance does not differ from the silence condition. At high ventilation rates the expected long-term annoyance increases.

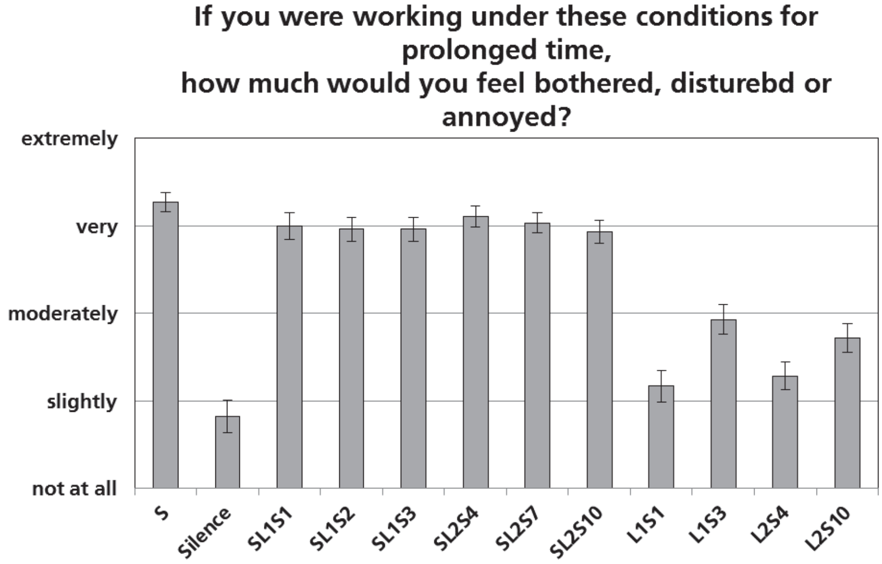

Figure 7 – The figure shows the expected long-term annoynace during the different experimental conditions.

3.2.5 Perceived performance

The comparison of the perceived performance during the different experimental conditions by a one-way ANOVA (repeated measures) revealed a significant main effect of the factor sound condition on the dependent variable perceived performance (F (11.297) = 9:32, p <.000, η2 =. 257). The perceived performance does not differ if pure ventilation sounds are compared to silence. The perceived performance during the unmasked and the masked speech conditions also does not differ.

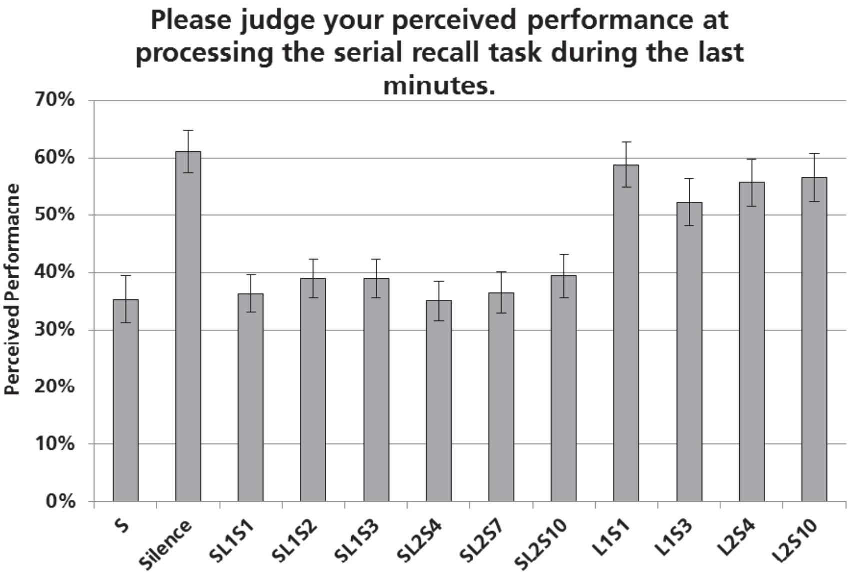

Figure 8 – The figure shows the perceived performance during the different experimental conditions.

4. CONCLUSIONS

The pure ventilation sounds were classified more annoying than Silence. However, the error rates during the serial recall task reveal that cognitive performance is not affected by the pure ventilation sounds, even if the ventilation units are operated at the highest level. One ventilation sound even helps to improve performance as compared to unmasked speech. Unlike to the judgement of annoyance, the concentrativeness is not considered worse during the presentation of pure ventilation sound as compared to Silence. In addition, the ventilation sounds of both ventilation units reduce the perceived annoyance caused by the speaker if they are run at medium or high ventilation rate. Therefore, if background speech is present, ventilation sounds help to reduce perceived annoyance and may even improve performance. There are also hints towards improved privacy under presentation of the high volume ventilation sound of one ventilation unit as the estimated distance to the speaker increases. However, if ventilation sounds are presented without background speech, they are perceived to be more annoying than Silence. This especially applies for the higher volume ventilation sounds with regard to long-term annoyance.

These results support the idea that there should not be a static target value for ventilation sounds but instead they should be used adaptively as a means of conditioning room acoustics. However, the results must not be interpreted in a way that it suffices to just run ventilation units at the highest ventilation rates in order to mask disturbing background speech. Instead ventilation sounds should be designed in order to produce good results with regard to masking speech but at the same time remain pleasant if they are presented solely. The project also reveals that it is necessary to reconsider the spectral characteristics since only one ventilation unit helps to improve performance and privacy even so the A-weighted levels of the two ventilation units are very much the same. The next steps will include targeted conditioning of the signal to noise ratios and spectral characteristics of ventilation sounds and additionally field tests are desirable.

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