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Adaptive Volume Control for Sound Masking

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ABSTRACT

Basic sound masking systems were introduced in the 1970s to improve speech privacy in open plan offices. Since then, various features were introduced to improve the efficiency and performance of sound masking systems. Amongst other things, the need to increase and decrease the masking sound level depending on the activity and noise level within the workspace was addressed. Today, most sound masking system controllers permit complex time/level programs to be stored and used for different office zones.

The aim of this paper is to show how the real-time analysis of the sound level distribution in the open-plan office environment can be used to efficiently adapt and control the volume of the masking sound. The effect of various parameters that can be used to modify the rate of sound level increase/decrease is also presented. The number of sound level sensors required per zone is also discussed.

Results obtained on various installations are analyzed and presented, and the performance of the Adaptive Volume Control (AVC) feature is compared to timer-based functions.

1. INTRODUCTION

The principle of sound masking is the emission of a soft, neutral and non-disturbing sound to mask noise distractions, mainly voices travelling throughout the office, in order to improve confidentiality and productivity.

Since its introduction, various features were added to improve the performance of sound masking systems. Amongst other things, the need to increase and decrease the masking sound level depending on the activity within the workspace was recognized and programmable timer functions were introduced[1]. Today, the specifications for a sound masking system generally request a timer function, so as to allow for the setting of the masking volume according to a schedule for each independent zone.

Typically, the timer function is set-up to increase the volume in the morning and decrease it during the lunch period and at nighttime. The effectiveness of the timer function assumes that the activity levels are relatively constant during the workday. This assumption can however be put in doubt, especially in modern offices where various working behaviors can take place.

2. VARIABILITY OF DAYTIME NOISE LEVELS IN OPEN PLAN

Bradley[2] showed, using measurements spread over 700 open offices, that average daytime sound levels in an open-plan office vary with an almost normal distribution between 38 and 55 dBA (90% of values contained within this range). The question here is to what extend these sound levels are constant or vary throughout the working hours. To answer this question, the noise levels in various open spaces were analyzed. The noise levels were measured just below the suspended ceiling to avoid the effect of a local sound source (such as a voice coming mainly from a given workstation) and to obtain as much as possible the cumulative level of voices coming from different workstations.

Figure 1 presents typical results obtained for a) a small open space (10 workstations), b) a medium open space (20 workstations), and c) and d) two different locations within a large open space. The graphs on the left present the $L_{Aeq,1h}$ over a week, and the graphs on the right present the statistical distribution of the levels over the working hours period (8:30AM - 5:00PM, Monday to Friday).

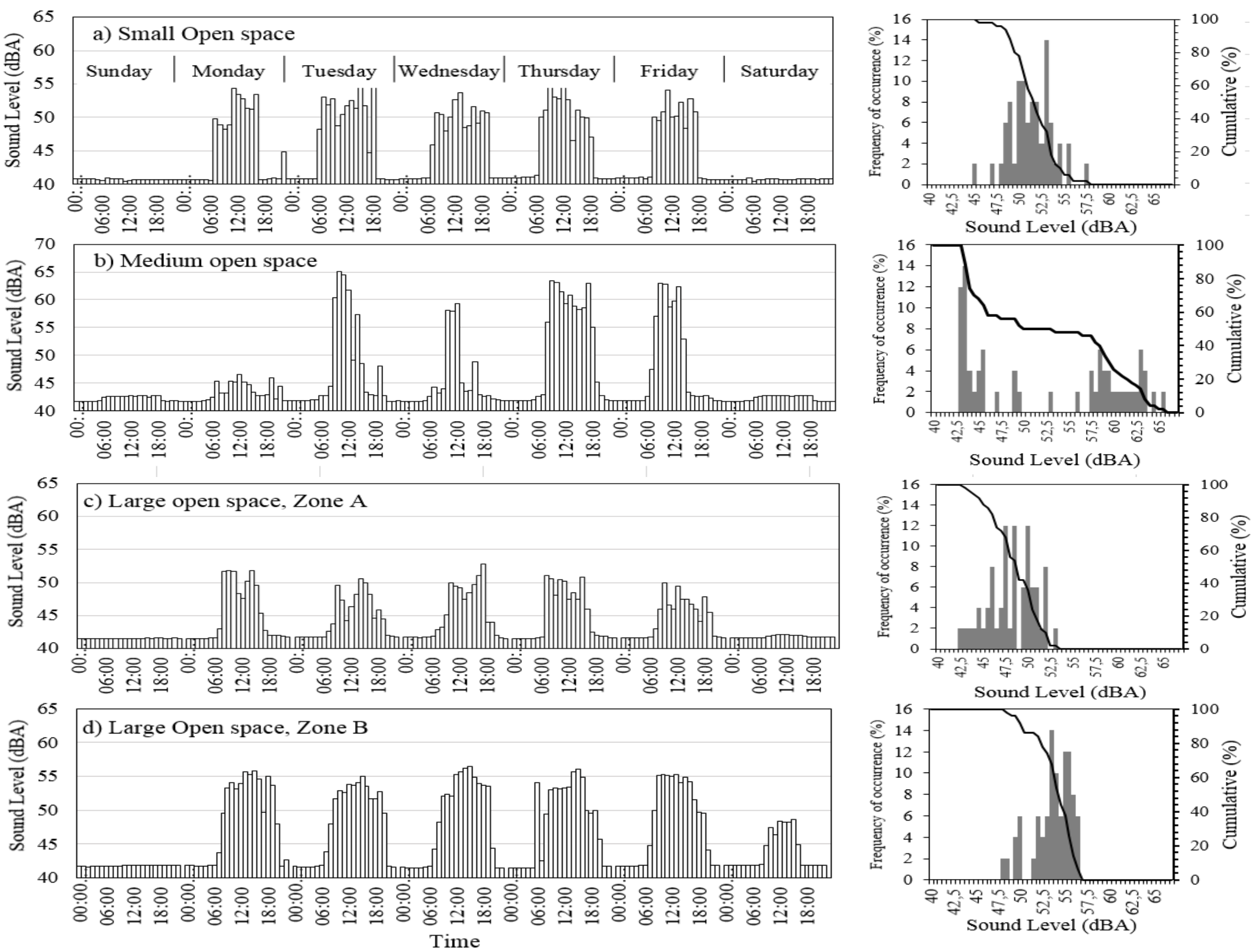

Figure 1 $L_{Aeq,1h}$ over a week, and their statistical distribution over the working hours period (8:30AM - 5:00PM, Monday to Friday) for a) a small open space, b) a medium open space, and c) and d) two different locations within a large open space.

Obviously, the $L_{Aeq,1h}$ noise levels are higher during working hours, typically between 8:30AM and 5:00PM, but there are significant variations from hour to hour, from one day to another, and from one location to another. The statistical distribution of the $L_{Aeq,1h}$ is approximately normal, with a standard deviation of about 10 dB in all cases. It can also be observed that in zone B of the large open office, the noise levels due to activity were significant on Saturday (a call center department).

If $L_{Aeq,15m}$ levels are considered instead of $L_{Aeq,1h}$, more variations can be observed (see Figure 2). This is simply the consequence of noise events within workspaces (most of the time due to people talking) starting and stopping intermittently. If $L_{Aeq,5m}$ levels are considered, the variation becomes even more important.

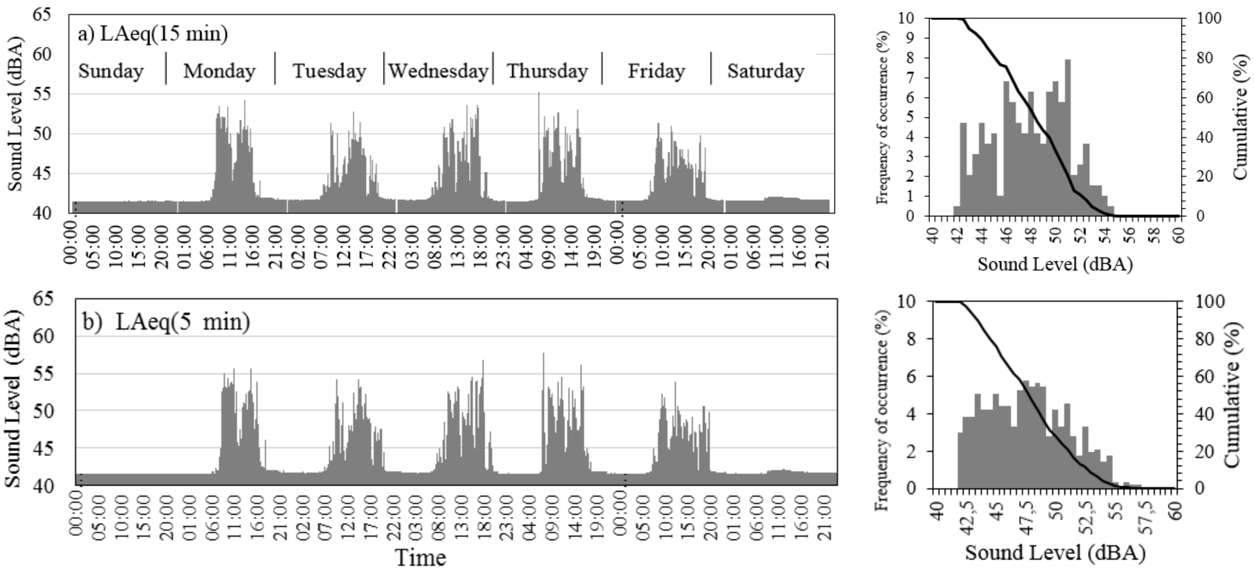

Figure 2: a) $L_{Aeq,15m}$ and b) $L_{Aeq,5m}$ in zone A of the large open office of Fig. 1c, and the statistical distribution during the working hours (8:30AM - 5:00PM, Monday to Friday).

3. AUTOMATIC VOLUME CONTROL

A. Timer Function Volume Control

A timer function volume control typically increases the sound volume in the morning and lowers it during lunchtime and in the evening for nighttime. While being very simple to implement, this timer function lacks the ability to adapt to the varying activity levels of the modern office environment. The predefined masking sound level can be too high in low-activity environments and too low in high-activity environments. Furthermore, they need to be reconfigured if a change in work hours occurs.

B. Conventional Automatic Volume Control

A conventional automatic volume control, like those used for the television sets in waiting rooms, are analog devices that can increase or decrease the volume according to the instantaneous ambient sound pressure level (SPL). However, these devices rapidly respond to short noise events, and can increase (or decrease) the masking sound level sharply and significantly, 3 dB or more in a couple of seconds. Such variations of the masking sound levels are clearly perceived by the users and lead to discomfort. These volume controllers are thus not well adapted for sound masking systems.

C. Automatic Volume Control Based on Statistical Analysis

In an effort to correct the problems related to conventional automatic volume controls, an automatic volume control algorithm based on the statistical analysis of the SPL was developed[3].

Figure 3 shows the SPL fast measured in an open-space for a typical morning. When there are few disruptive noises in an office (few conversations and intermittent noises), the noise levels are quite stable and the statistical distribution of sound levels is small (Figure 3a). On the contrary, when the voices and/or noises due to human activities increase, important variations occur and the statistical distribution of the sound levels is significantly larger (Figure 3b).

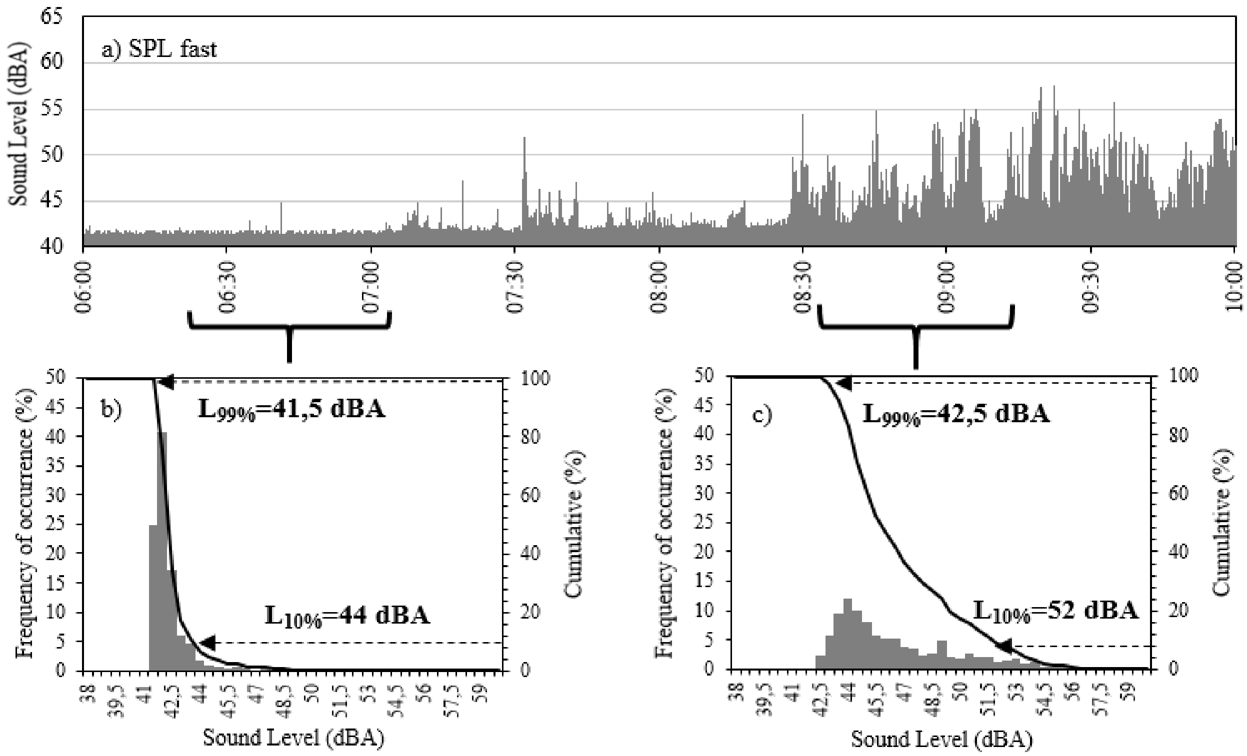

Figure 3: SPL fast for a typical morning, and the statistical distribution of the noise levels a) before and b) after an increase in voices and/or noises due to human activities.

Few speech or noise events result in a small difference between the L10% and L99%, whilst many speech or noise events will lead to a large difference between L10% and L99%.

The difference between the percentile levels L10% and L99%, denoted $\Delta L10\text{-}99$, thus appears to be an efficient parameter to evaluate the level of disturbing noise in an office.

Adaptive Volume Control (AVC) of Masking Sound Level

When disturbing noise events increase, the $\Delta L10\text{-}99$ increases and the sound masking level should be increased. When the $\Delta L10\text{-}99$ decreases, the sound masking level should be reduced. To obtain the desired behavior, the following function can be used:

$$AVC\ (dB) = W * (\Delta L10\text{-}99 - TgL10\text{-}99) \qquad \text{eq. 1}$$

$TgL10\text{-}99$ is the target difference between L10% and the L99%. When $\Delta L10\text{-}99 - TgL10\text{-}99$ is positive, the system increases the sound masking accordingly. If the difference is negative, the system decreases the masking sound level. W is an adjustable factor that allows weighting the resulting difference, making the system either more or less sensitive.

As an example, if $TgL10\text{-}99$ is set to 10 dB and the system measures a $\Delta L10\text{-}99$ of 15 dB (an acoustical environment with significant noise events) and with a weighting factor W set to 0.5, the algorithm will set the increase of the masking level to AVC Gain = 2.5 dB.

Statistical Analysis Time Period

The length of the time period considered for the statistical analysis, TSA, will determine the sensitivity of the system to react to sporadic noise events or to more general trends in changes of the acoustic environment. A short TSA will make the system react rapidly to sporadic noise events, whereas a longer TSA will allow the system to react to longer trends of the acoustic environment. Evaluations done on many sound masking installations have shown that a TSA of 15 seconds provides a rate of change well adapted for most office noise behaviors.

Maximum Change Rate

To ensure a smooth and undetectable variation of the masking sound volume, the change rate in dB/s can be set. For instance, if the controller requests an AVC gain of 3 dB and if the maximum Up-Rate is set to 0.05dB/s, the sound masking will take about 1 minute to reach 3 dB. In a working environment, such a change is imperceptible to the great majority of people.

Maximum and Minimum Masking Sound Level

To avoid any discomfort, the masking sound level must be limited to a maximum and minimum level. The maximum masking sound level depends on the desired masking effect and degree of comfort. These values may be specified by an acoustician. Typically, the maximum masking sound level should be set to 45 dBA for an optimal sound masking effect, and up to a maximum of 48 dBA. Above this 48 dBA limit the sound masking itself may cause discomfort[4].

The minimum masking sound level preserves a minimum degree of confidentiality and a comfortable acoustical environment. Based on our experience on hundreds of installations with AVC control, a sound masking level of 42 dBA in a calm open-plan office creates a smooth acoustical environment that is appreciated by the occupants. Nevertheless, this minimum masking level can be set to meet the needs of the consultant's specifications.

Effect of Different Parameters on the Adaptive Volume Control Algorithm

To present the effect of the *TgL10-99* and *W* parameters of the AVC algorithm, the results obtained in medium size open-plan offices (Fig. 1b) will be used since there are different levels of activities from one day to another (from calm to relatively noisy).

Figure 4a presents the $L_{Aeq,15s}$. The average noise level for the whole working day (8:30AM - 5:00PM, Monday to Friday) is provided on the top of the Figure. This daytime equivalent level provides an indication of the degree of noisy activities during the day. Figure 4b presents the adaptive volume adjustment obtained with the standard parameters of the AVC algorithm: *TgL10-99* = 7.5 dB, *W* = 0.5, step-up & down of 0.025 dB/s. The minimum masking sound level is 42 dBA and the maximum is 45 dBA (hence 3 dB of adaptive volume control). Figure 4c uses a smaller value of *TgL10-99* = 3 dB. Figure 4d shows the effect of a large weighting factor (W= 4).

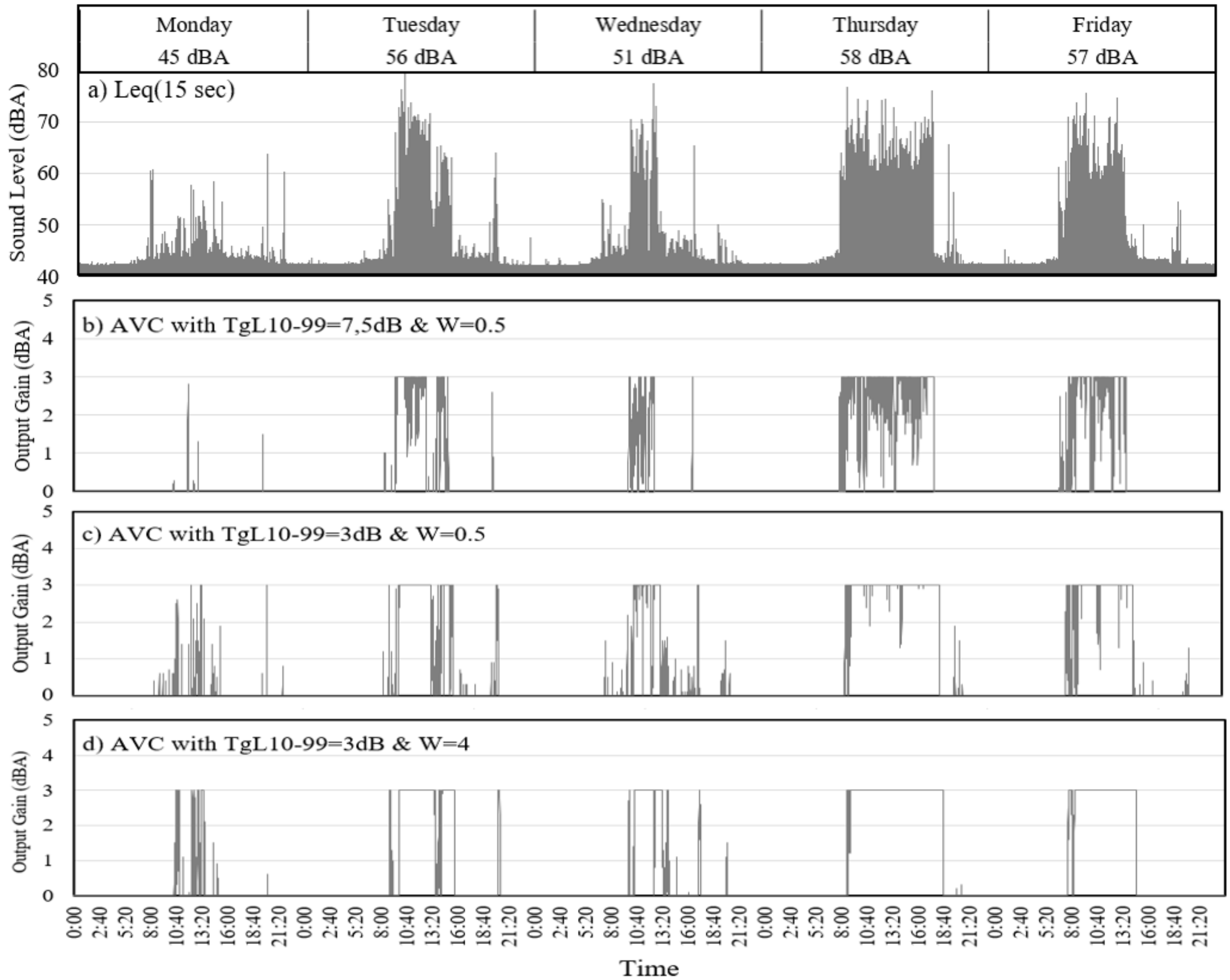

Figure 4 $L_{Aeq,15s}$ and average noise levels for the whole working day (8:30AM - 5:00PM, Monday to Friday) is provided on the top of the Figure. Figure 4b Volume Adjustment obtained with standard parameters: *TgL10-99* = 7.5 dB, *W* = 0.5. Figure 4c) same as previous, but *TgL10-99* = 3 dB, and 4d) *TgL10-99* = 3 and W= 4

If *TgL10-99* is reduced to 3 dB instead of 7.5 dB, the control algorithm will increase the sound masking even if there are only a few noise variations (Fig. 4c). If the weighting factor *W* is set to 4 instead of 0.5, the volume control becomes more sensitive (Fig. 4d). In this situation, it reacts essentially like a timer control with an on/off behavior but with greater intelligence since the masking sound level is set at its minimum when there are no disturbing noises (such as Monday morning in the previous example). The adaptive volume control algorithm thus provides a very high degree of flexibility and control.

An extensive evaluation on more than 500 sound masking installations led to the following parameters, which optimized the acoustical comfort and degree of speech privacy. These optimized parameters are: *TgL10-99* = 7.5 dB, *W* = 0.5, and maximum volume change rate of 0.025 dB/s.

In practice, the parameters of the AVC are set to these default values and, generally don't require adjustments. The efficiency of the sound masking systems on the acoustical comfort and speech privacy can however be evaluated after a while using the data obtained on site.

4. EVALUATION OF COMFORT AND SPEECH PRIVACY

Improvement of Acoustical Comfort

As describe by Bradley[4], "The degree of acoustic comfort in an open-plan office is related to the combined effects of unwanted ambient noise and a desired level of speech privacy."

It is generally accepted that a masking sound level of 45 dBA is considered optimum and 48 dBA the upper limit over which sound masking itself may cause discomfort[4].

That being said, if the overall noise level (L_{Aeq}) in the office is significantly higher than the sound masking level (Lmk) the sound masking itself will not be noticeable by the occupants and will not generate discomfort even if it is higher than 45 dBA. However, if the acoustical environment is calmer with only a few disturbing noise events, the L_{Aeq} will be more or less equal to the Lmk and the masking sound may be more noticeable and could generate discomfort even if it is set to 45 dBA.

Hence, in an effort to give more nuances to the general guideline, the difference between the ambient sound level L_{Aeq} and the masking sound level Lmk (ΔL_{Aeq}-Lmk) appears therefore to be an appropriate parameter to evaluate the discomfort related to the sound masking.

The minimum ΔL_{Aeq}-Lmk where discomfort may begin to appear is however subjective. Considering that 0 dB means that the masking sound is the most significant sound of the environment, and that a difference of 10 dB makes the masking sound almost undistinguishable compared to the overall ambient noise, a value of 5 dB for ΔL_{Aeq}-Lmk appears to be a reasonable value to evaluate at what point any discomfort due to the dominancy of the masking sound may occur. In addition, it can be agree that a low level of masking sound will not create any significant discomfort (about 42 dBA according to our experience). A masking sound level lower than 42 dBA (Lmk<42 dBA) should therefore be considered as comfortable even if the L_{Aeq} is not 5 dB above Lmk.

Table 1 below presents the percentage of the time for which the comfort criteria was respected (L_{Aeq}-Lmk > 5dB || Lmk < 42dBA) for the five working days of Fig 4. Each column presents the results for the different days as a function of increasing noise activity. The results are provided for a constant masking sound level of 45 dBA (as would be provided by a timer function), and for two Adaptive Volume Control with different maximum limits: 42-45 dBA, and 42-48 dBA.

Table 1: Evaluation of Comfort: Percentage of time respecting the comfort criteria

Leq (8h30 - 17h)	**Calm** → **45 dBA** (Monday)	**51 dBA** (Wednesday)	**55 dBA** (Tuesday)	**57 dBA** (Friday)	**Active** **59 dBA** (Thursday)
Timer constant 45 dBA	2%	31%	56%	45%	92%
AVC with 42 to 45 dBA limits	98%	98%	94%	96%	97%
Improvement on comfort	96%	67%	39%	51%	5%
AVC with 42 to 48 dBA limits	98%	97%	94%	96%	96%
Improvement on comfort	96%	67%	39%	51%	4%

Note that if a value of 3 or 10 dB is considered for the L_{Aeq}-*Lmk* parameter instead of 5 dB, the % time where the comfort criteria is respected will change, but the improvement in comfort from the timer function to the AVC will be similar.

The results of Table 1 show that, in a calm environment (Daytime L_{Aeq} of 45 dBA), the comfort criteria are respected only 2% of the time when using a fixed sound masking level of 45 dBA provided by a timer function. By contrast, with the AVC set to 42-45 dBA, the comfort criteria are respected almost 98% of the time, which is an improvement of 96% compared to the constant masking volume. In a moderately active day (Daytime L_{Aeq} of 51, 55 and 57 dBA), the improvements in comfort are respectively 67%, 39% and 51%. For a very active day (Daytime L_{Aeq} of 59 dBA), the improvement is less significant (5%), which is to be expected as the masking level reaches 45 dBA for almost the entire day.

Improvement in Speech Privacy

Standardized methods exist to evaluate the speech privacy between two closes offices or workstations[5,6,7]. However, these methods cannot be applied by using the overall noise level measured just under the suspended ceiling, the data available in this study. To evaluate the improvement (or reduction) in speech privacy provide by the AVC compared to a constant sound masking level, it appears reasonable to compare how often the L10% significantly exceeds the masking level Lmk of both systems. For the purpose of this analysis, the criteria *L10%<Lmk+15 dB* was considered. Essentially, the more often the criteria is met, the better the privacy should be.

Table 2 presents the percentage of the time for which the *L10% <Lmk+15dB* for the five working days of Fig 4. Each column presents the results for the different days as a function of increasing noise activity. The results are provided for a constant masking sound level of 45 dBA provided by a timer function and for two Adaptive Volume Control maximum limits: 42-45 dBA and 42-48 dBA.

Table 2: Evaluation of Privacy: Percentage of time respecting the privacy criterion *L10% <Lmk+15dB*

Leq (daytime:8h30-17h)	**Calm** **45 dBA** (Monday)	**51 dBA** (Wednesday)	**55 dBA** (Tuesday)	**57 dBA** (Friday)	**Active** **59 dBA** Thursday
Constant Lmk: 45 dBA	100%	92.1%	68.7%	72.7%	51.3%
AVC with 42-45 dBA limits	99.8%	91.9%	68.6%	72.2%	51.0%
Improvement on privacy	-0.2%	-0.2%	-0.1%	-0.5%	-0.3%
AVC with 42-48 dBA limits	99.8%	93.4%	78.2%	79.8%	65.7%
Improvement on privacy	-0.2%	1.3%	9.5%	7.1%	14.4%

Note that if the exceeding values of 12 or 18 dB are considered instead of 15 dB, the % time respecting the comfort criteria will change, but the improvement in privacy from the timer function to the AVC will be similar.

When comparing the constant masking sound level of 45 dBA and the Adaptive Volume Control set to 42-45 dBA, the percentage of time that the privacy criterion is respected appears to be almost identical. In fact, the reduction of speech privacy appears to be less than 1% on calm, moderate, or active days. As such, it can be concluded that an AVC provides the same degree of speech privacy as a timer function that provides a constant masking sound level with the same higher limit.

If the higher limit of the AVC is increased to 48 dB instead of 45 dB, the percentage time the privacy criterion is respected goes from 72.2% to 79.8% (for a moderately active day) and from 51% to 65.7% (for the high activity day). This improvement can be interpreted as an increase on speech privacy of 7.1% and 14% for days of moderate and high activity respectively. And as shown in Table 1, this improvement in speech privacy can be obtained along with a significant improvement in the acoustical comfort.

5. CONCLUSION

To improve the acoustical comfort of a sound masking installation, the need to increase and decrease the masking sound level depending on the activity is well recognized. Since the end of the 1970's: programmable timer functions were developed to answer this need as much as possible. However, measurements done in modern open offices show that noise levels vary significantly during the day, and from one day to another.

To improve the effectiveness and comfort of sound masking installations, an Adaptive Volume Control algorithm has been developed. This AVC algorithm is based on real-time statistical analysis of the SPL and uses the difference between the L10% and L99% to set the volume adjustment. Parameters can be set to make the volume adjustment more or less sensitive to noise activities in the room to make the volume changes more or less responsive.

A number of simulations and analyses based on the noise levels measured on real sound masking installations were performed to determine the typical values of these parameters that optimize the acoustical comfort and privacy for most cases. An analysis of the difference between the ambient L_{Aeq} and the masking sound levels on various days with different levels of activity has been undertaken.

When the lower and upper limits of the AVC are set to 42 and 45 dBA respectively, the confidentiality obtained is almost identical to a constant masking level of 45 dBA as provided by a timer function. However the acoustical comfort is significantly improved when using the AVC in comparison to the timer, showing up to 50% improvement in acoustic comfort for periods of moderate office activity according to the criteria used in this study.

If the higher limit of the AVC is set to 48 dBA instead of 45 dBA, according to the criteria used in this study, then speech privacy will be improved by up to 15% in comparison to the timer function, without any significant reduction of the acoustical comfort.

6. REFERENCES

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