THE USE OF ADAPTIVE SOUND MASKING SYSTEMS IN OPEN-PLAN OFFICES: HOW THEY WORK, AND THE RELATIVE IMPROVEMENTS FOR SPEECH PRIVACY AND ACOUSTIC COMFORT

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1 INTRODUCTION

The principle of sound masking is the emission of a soft, neutral and non-disturbing sound to mask noise distractions, mainly speech travelling throughout the office, in order to improve privacy by reducing the incoming speech signal-to-noise ratio and thus intelligibility, as well as increase productivity through a reduction in distractions.

Sound masking systems are encouraged in state-of-the-art office design guidelines such as LEED V4.1[1] and WELL V.2[2]. Indeed, both performance standard documents allow for a 5-point reduction in the required minimum sound insulation rating (STC or Rw) when a masking system is adopted. Research studies by the National Research Council of Canada (NRCC) have produced optimum frequency spectrums and sound level ranges designed to balance occupant acceptance with effective speech privacy[3]. LEED V4.1 requires masking systems to be implemented at a minimum of 40 dBA using the NRCC spectrum, to a maximum of 48 dBA in open-plan offices. NRCC recommend 45 dBA as an optimum unoccupied background sound level, whilst the recently revised ISO 3382-3[4] recommends 40-45 dBA for good open-plan office conditions. The NRCC also noted that reducing continuous background sound levels from 45 dBA to 42 dBA will lead to a substantial decrease in speech privacy. WELL V.2 only sets out a maximum value of 48 dBA in open-plan offices, although with no minimum value. Both criteria documents specify a minimum frequency range of 100 Hz to 5000 Hz for effective sound masking. The more recent ISO 22955[5] attempts to recommend conditions for good offices acoustics but is undermined through its presumption that a minimum workstation background sound level between 40-48 dBA ($L_{Aeq,\,8h}$) is achieved by occupant-generated noise alone, i.e. without the use of sound masking. As the document itself notes, when open-plan office occupancy levels fall below 80%, speech privacy issues may result due to the background sound level falling below these assumed levels.

Since the 1970s, various features were introduced to sound masking systems to respond to varying occupancy conditions. Programmable timers were a response to the need to increase and decrease the masking sound level depending on the likelihood of disturbance within the workspace (i.e., lower background sound levels during low occupancy, higher background sound levels during high occupancy).[6] Today, sound masking system specifications will typically request a timer function as standard, to permit variable masking sound level according to an occupancy schedule for each separate work zone. Usually, the timer function is set-up to increase the sound level in the morning, and decrease it during lunch and nighttime periods. The effectiveness of the timer function assumes that the activity levels are relatively constant during the workday, and repeatable through the working week. This assumption was in doubt however even pre-pandemic, especially in offices with activity-based working. Post-pandemic, and in the age of hybrid working, average office occupancy rates in Montreal, Quebec for example are still only 20-30% office capacity on Mondays and Fridays as of Summer 2023, up to only 61% on the busiest days[7]. As a result, clearly variations in occupancy previously both day-to-day as well as within each day will likely only exacerbate the sound level variations.

2 VARIABILITY OF DAYTIME NOISE LEVELS IN OPEN PLAN

Bradley[8] showed in 2003, using measurements spread over 700 open offices, that average daytime sound levels (L_{Aeq}) 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. Yadav et al.[9] recently examined 43 open-plan offices across 9 buildings and found that whilst the mean $L_{Aeq,\ 4h}$ result was 53 dBA, the Mean $L_{A90,4h}$ was only 32 dBA.

In this paper, sound levels were measured across a 7-day period in 4 different open-plan offices in Quebec, Canada. The sound 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).

As would be expected, 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 range 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).

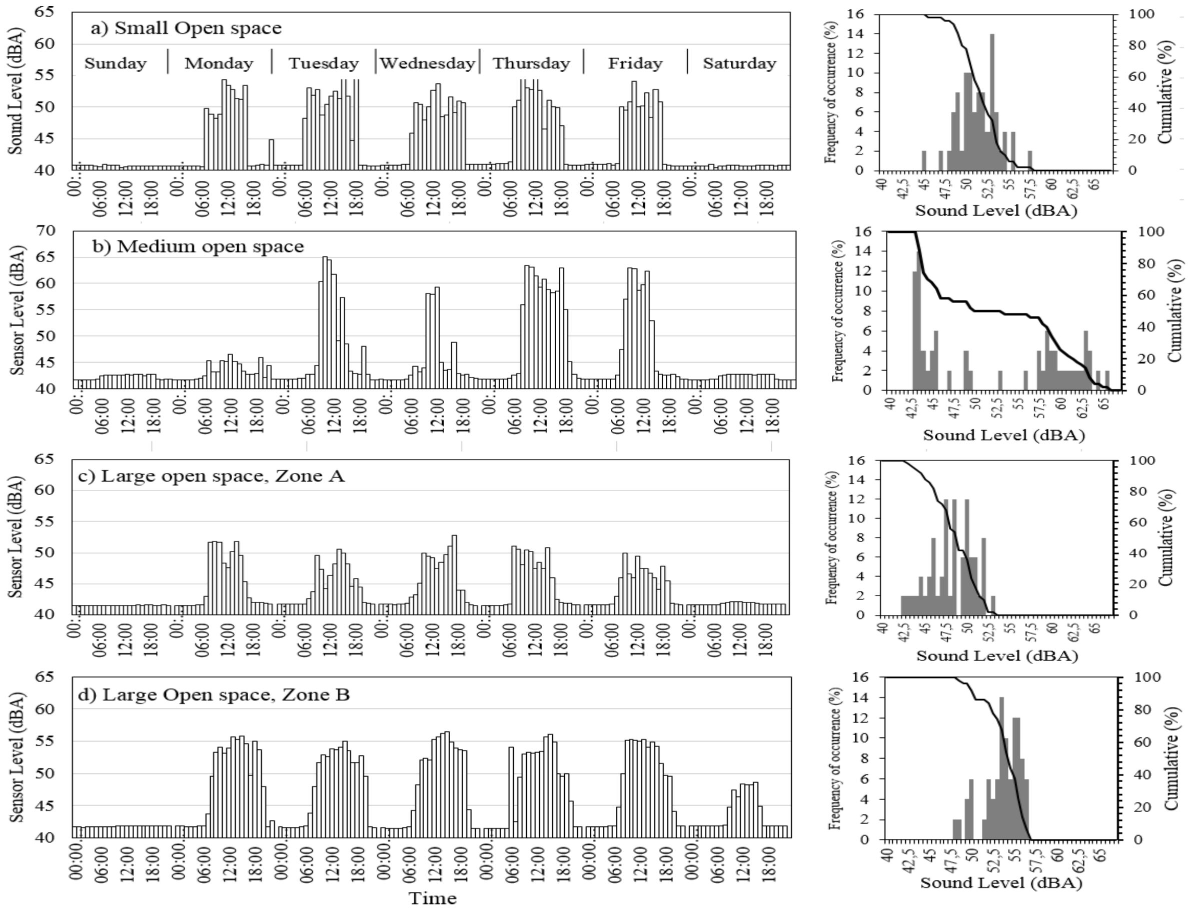

Figure 1 $L_{Aeq,1h}$ over a week, and their statistical distribution over the working hours period (8:30AM - 5:00PM, Monday to Friday) for a) a small open space, b) a medium open space, and c) and d) two different locations within a large open space.

If $L_{Aeq,15m}$ levels are considered instead of $L_{Aeq,1h}$, more detailed variations can be observed (see Figure 2). This is the consequence of noise events within workspaces (assumed to be speech communication) starting and stopping intermittently. If $L_{Aeq,5m}$ levels are considered, the variation becomes even more noticeable.

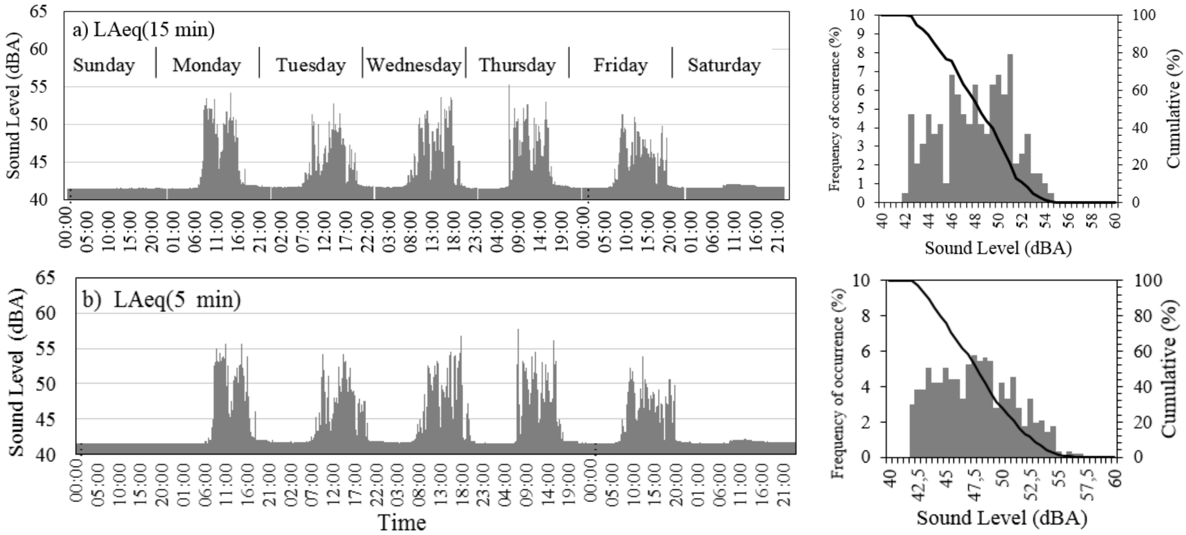

Figure 2: a) $L_{Aeq,15m}$ and b) $L_{Aeq,5m}$ in zone A of the large open office of Fig. 1c, and the statistical distribution during the working hours (8:30AM - 5:00PM, Monday to Friday).

3 AUTOMATIC VOLUME CONTROL

3.1 Timer Function Volume Control

As previously noted, timer function volume control typically increases the sound level 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/occupancy periods and too low in high-activity environments/occupancy periods. Furthermore, they need to be reconfigured if any changes estimated work hours occurs.

3.2 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 whose strength should be in the relative imperceptibility.

3.3 Automatic Volume Control Based on Statistical Analysis

In an effort to address these problems related to conventional timer based or automatic volume controls, an automatic volume control algorithm based on the statistical analysis of the SPL was developed[10].

Figure 3 shows the SPL (fast) measured in an open-space for a typical morning. When there are few disruptive noises in the office (few conversations and intermittent noises), the sound 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).

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 Δ*L10-99*, thus appears to be an efficient parameter to evaluate the level of disturbing noise in an office. Indeed, a similar metric, the Noise Climate, NCI (*LA10-LA90*) was proposed in the study by Yadav et al.[9] as a metric to observe the likelihood of auditory distraction in real world offices.

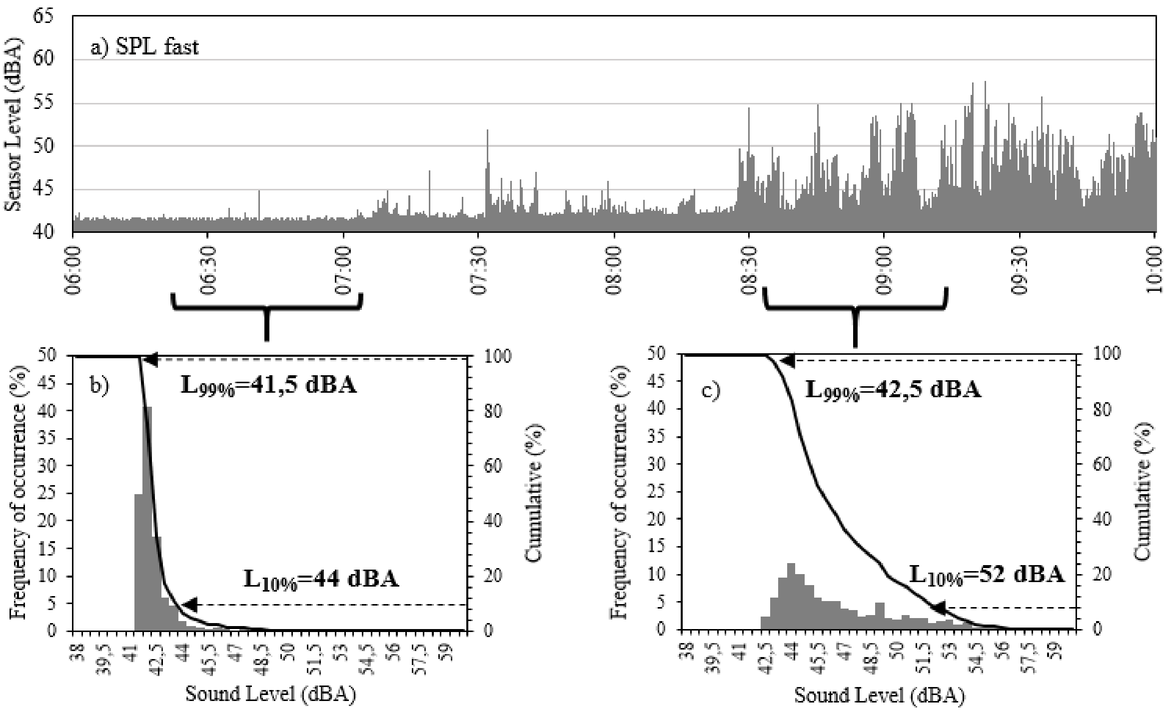

Figure 3: SPL fast for a typical morning, and the statistical distribution of the noise levels a) before and b) after an increase in voices and/or noises due to human activities.

3.3.1 Adaptive Volume Control (AVC) of Masking Sound Level

When disturbing noise events increase, the Δ*L10-99* increases and thus the sound masking level should be increased to reduce the incoming speech signal-to-noise ratio. When the Δ*L10-99* decreases, the sound masking level should be reduced as the higher level is no longer required. To obtain the desired behavior, the following function can be used:

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

In this equation, *TgL10-99* is the target difference between L10% and the L99%. When $\Delta L10\text{-}99$ – *TgL10-99* 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 *TgL10-99* is set to 10 dB and the system measures a $\Delta L10\text{-}99$ of 15 dB (i.e., an acoustic environment with significant noise events occurring) 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.

3.3.2 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 performed by the developers on many sound masking installations, in conjunction with feedback from the end-users, allowed for the determination that a TSA of 15 seconds provides a rate of change well adapted for most office noise behaviors.

3.3.3 Maximum Change Rate

To ensure a smooth and undetectable variation of the masking sound level, 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 typical working environment, such a change is imperceptible to the great majority of people.

3.3.4 Maximum and Minimum Masking Sound Level

To be effective, 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, and as per NRCC studies[3], 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. At or above this 48 dBA limit the sound masking itself will begin to lead to decreased occupant satisfaction[3].

The minimum masking sound level preserves a minimum degree of speech privacy and reduction in distractions. Whilst LEED V4.1[1] recommends a minimum 40 dBA, NRCC[3] note that speech privacy is substantially reduced at 42 dBA relative to 45 dBA. Indeed, background levels below this would make achievement of the ISO 3382-3 recommended distraction distance (<5m) very difficult to otherwise achieve in most open-plan offices. A recent subjective study by Lee et al.[12] across large open-plan offices determined that a masking level of 42 dBA was found to be more pleasant and less distracting than at 47 dBA, whilst both masking sound conditions scored more highly than when the masking system was muted (residual level approximately 38 dBA). Nevertheless, this minimum masking level can be set to meet the needs of the acoustical consultant’s specifications.

3.3.5 Effect of Different Parameters on AVC 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 $L_{Aeq,15s}$ (i.e. the chosen TSA of the system). The average sound level for the whole working day ($L_{Aeq,\,8.5h}$, 8:30AM - 5:00PM, Monday to Friday) is provided on the top of the Figure. This daytime equivalent level does provide an indication of the degree of noisy activities between the days, but not the inherent variation in levels within that 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).

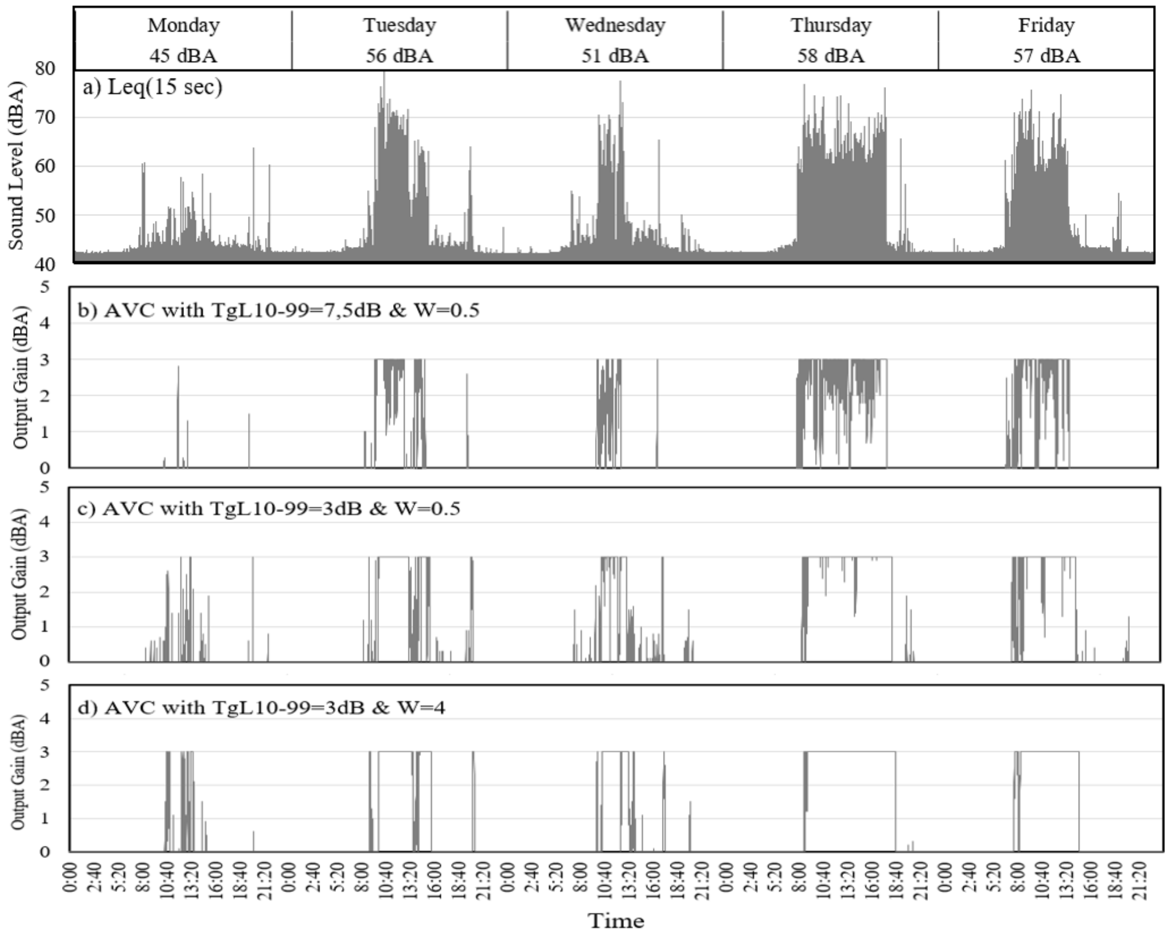

Figure 4. $L_{Aeq,15s}$ and $L_{Aeq,8.5h}$ per day (Figure 4a). Figure 4b Volume Adjustment obtained with standard parameters: *TgL10-99* = 7.5 dB, *W* = 0.5. Figure 4c) same as previous, but *TgL10-99* = 3 dB, and Figure 4d) *TgL10-99* = 3 and W= 4

It can be seen that 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 can thus provide a high degree of flexibility and control in response to occupied noise levels. Evaluations of more than 500 sound masking installations led to the following parameters shown in Figure 4b being determined as optimal to balance the acoustical comfort and degree of speech privacy and thus applied as default for AVC: *TgL10-99* = 7.5 dB, *W* = 0.5, and maximum volume change rate of 0.025 dB/s.

The efficiency of the sound masking systems on the acoustical comfort and speech privacy can however be evaluated using the data obtained on site from the ceiling-mounted sound level sensors.

4 EVALUATION OF COMFORT AND SPEECH PRIVACY

4.1 Effect on Acoustic Comfort

As describe by Bradley[8], “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 to achieve this balance and 48 dBA represents an 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 occupant discomfort related to the presence of the sound masking.

However, the minimum ΔL_{Aeq}-Lmk where discomfort may begin to appear is subjective. Considering an ΔL_{Aeq}-Lmk = 0 dB would mean that the masking sound is the dominant sound in the office environment, and that an ΔL_{Aeq}-Lmk = 10 dB means the masking sound has almost no contribution to the overall ambient noise, then a value of 5 dB for ΔL_{Aeq}-Lmk appears to be a reasonable value to evaluate at what point any discomfort due to an increasing contribution of the higher level of masking sound may occur. Whilst ISO 3382-3[4] introduces the comfort distance metric as the level at which intruding speech falls below 45 dBA, 42 dBA is taken in this study as a lower limit for occupant discomfort based on NRCC guidance that levels lower than this significantly reduce the effectiveness of sound masking for speech privacy (this is supported by the findings of Haapakangas et al.[13] and Lee et al.[12] wherein lower residual background sound levels were found to be associated with a higher degree of noise disturbance. 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 (i.e. L_{Aeq}-Lmk > 5dB || Lmk < 42dBA) in the medium size open-plan office 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 (i) 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: (ii) 42-45 dBA, and (iii) 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 relative to timer constant	96%	67%	39%	51%	5%
AVC with 42 to 48 dBA limits	98%	97%	94%	96%	96%
Improvement on comfort relative to timer constant	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 relative to the timer function to the AVC would be similar.

The results of Table 1 show that, in a calm daytime environment in the medium open-plan office (daytime $L_{Aeq,\ 8.5h}$ 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, timer-based masking level. For 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 adaptive masking level reaches 45 dBA for almost the entire day.

4.2 Effect on Speech Privacy

Standardized ISO and ASTM methods exist to evaluate the speech privacy between two workstations or to categorize the workspace as a whole[4,14]. However, these methods cannot be applied by using the overall noise level measured just under the suspended ceiling, which is 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, as +15 dB is generally taken to represent excellent speech intelligibility in a signal-to-noise ratio. Essentially, the more often the criteria are met, the better the speech privacy should be.

Table 2 presents the percentage of the time for which the *L10% <Lmk+15dB* for the five working days of Figure 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 Speech 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 (less than 1% reduction). As such, it can be concluded that an AVC provides effectively 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 CONCLUDING REMARKS

To improve the acoustical comfort of a sound masking installation, the need to increase and decrease the masking sound level depending on the activity and occupancy 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 preformed in modern open offices show that noise levels vary significantly during the day, and from one day to another. This is particularly true post-COVID-19 pandemic where occupancy rates fluctuate significantly from day to day.

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 open-plan office 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. 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 speech privacy obtained is almost identical to a constant masking level of 45 dBA (as provided by a common timer function). However, the occupant acoustical comfort is significantly improved when using the AVC in comparison to the timer, showing up to a 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.

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