TOWARDS MINIMAL LOUDNESS SOUND MASKING TO ENHANCE SOUND COMFORT IN OFFICES: AN EXPLORATORY EXPERIMENT

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ABSTRACT

Noise is a persistent issue in indoor environments like shared offices, where acoustic treatments may not provide sufficient auditory comfort. This paper explores two types of masking to enhance the perception of specific sound sources in the office through an exploratory experiment. The *masker* approach represents a traditional way to do sound masking; superimposing an existing sound to a noise to create a more pleasant mixture. Such an approach can be effective but will increase overall sound levels.

We propose an alternative approach, termed *concealer*, where we seek to adapt the spectro-temporal structure and content of the added sound to that of the noise, in order to reduce annoyance while minimizing overall loudness. Sound mixtures were generated using two ventilation noises and five water sounds across the two approaches and perceptually evaluated for their pleasantness. While no significant difference was found between proposed approaches, we find that more important variations in pleasantness are linked to the type of water sound.

1. INTRODUCTION

With their development and popularity, open-plan offices are today widely used for digital work. Although these workspaces have created a sense of conviviality and sharing, some comfort issues have emerged quickly. In particular, noise exposure during the work period can create stress that leads to reduced performance, provokes annoyance responses, and changes in social behavior [1]. Furthermore, people seem to be more and more aware of the impact of sound environments quality on their well-being, which appears to be a complex problem based on multiple factors.

During the past few years, research on open-plan offices has helped gather some important information about employee satisfaction (see [2]). Therefore, some improvement approaches have been proposed, mainly considering acoustic treatments that help reduce the overall level and intelligibility of speech. Although such treatments provide better privacy for employees [3], they may not be sufficient to ensure sound comfort, as annoyance can come with specific sound sources even if their level is satisfactory. In fact, various factors must be considered, such as the temporal and spectral properties of the sound [4]. Furthermore, as listening is a meaningful experience, the informational content of the sound was shown to have an effect on pleasantness [5, 6]. On top of that, quiet environments can reinforce the problem as it may make way for saliencies that are unpredictable and very annoying to workers.

Recently, sound masking systems have been developed to reduce speech intelligibility and improve privacy by adding background noise. Although adding sounds increases global level, it may help to make sound environments more pleasant. Valérian Fraisse notably demonstrated in his thesis that sound installations can improve the perception of urban soundscapes [7]. However, many studies conducted in open-plan offices obtained mixed results. For example, Hongisto and Haapakangas [8] set a condition for their positive results, that is, the background noise level was low in the office they studied, while Vassie and Richardson [9] and Bergefurt et al. [10] later observed both positive and negative effects for their level-adaptive sound masking. In fact, short-term mental health aspects were rated more positively after the application of the system, but employees felt more disengaged as masking sounds were presented through earphones. These results question the conditions under which masking systems are really relevant. Patrick Chevret especially highlighted the importance of different types of work activities by proposing a typology of open-plan offices in his recommendations [3]. Most of the studies we cited also concluded that context elements (people, activities, sound sources, layout, etc.) must be carefully studied, as the perception of sound is different between individuals but also between environments.

In this paper, we present an experiment to explore an original sound masking approach that aims at enhancing a noise source with minimal loudness addition. With this approach, termed *concealer*, we seek to work with added levels lower than 3dBA by adapting the spectro-temporal structure of the added sound to that of the noise source. Such an approach is defined in Section 2, as well as a traditional masking approach named *masker*. Both approaches are used to generate sound mixtures between ventilation noises and different types of water sounds, and the exploratory experiment presented in Section 3 is conducted to investigate the efficiency of the *concealer* approach. No significant difference is found between the two approaches. Moreover, although none of the approaches has a positive effect on participants' pleasantness judgments of the mixtures, the results presented and discussed in Section 4 and 5

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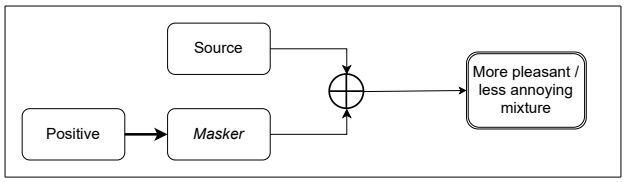


Figure 1. Principle of the *masker* approach: the *Masker* is a positive sound added to the noise source to make a more pleasant or less annoying sound

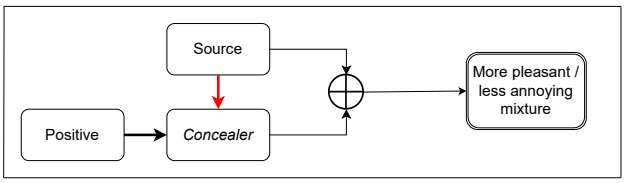


Figure 2. Principle of *concealer* approach: the *Concealer* adapts its spectro-temporal structure to blend with the noise and reduce its annoying aspect when added to it

reveal an effect of the type of water sound on pleasantness.

2. TWO SOUND AUGMENTED REALITY APPROACHES

We can use different techniques to do sound masking. Among them, energetic masking is clearly defined to cover annoying sounds with some spectral energy, notably by Fastl and Zwicker in their book *Psychoacoustics: Facts and Models* [11]. Matthieu Duroyon more recently defined other types of sound masking during his thesis, including what he called "masking by dressing" [12]. In this section, we define a *masker* approach that represents a traditional way to do energetic sound masking, and a *concealer* approach that formalizes and extends Matthieu Duroyon's idea by considering it as concealment.

2.1 The *masker* approach

2.1.1 Definition

The *masker* approach consists in adding a *Masker* to a noise source so it can hide it and create a mixture that will be perceived as more pleasant or at least less annoying. This *Masker* is an existing sound, and more precisely a positive sound that is assumed to be commonly accepted and pleasant, as shown in Figure 1. This idea of positive sound is inspired by the methodology used by Cai et al. in their study to investigate the effect of sound masking by adding water sounds to an industrial noise [13]. In fact, in the context of this study, water sounds are considered as pleasant sounds and help reduce the perceived annoyance induced by an electric welding noise, even if their addition to the sound environment increases its overall level.

2.1.2 Implementation

To generate some sound mixtures with the *masker* approach, a noise source and a positive sound are needed. If we note s as the source, m as the *masker*, and p as the positive, we simply pose $m = p$, and generate a mixture by adding the source and the *masker* $(s + m)$.

2.2 The *concealer* approach

2.2.1 Definition and objective

Instead of simply adding a positive sound to a noise source to make it more pleasant, the *concealer* approach introduces the idea of completing the noise source by considering the characteristics that make it perceptually negative. The added sound, named the *Concealer*, is constructed from the same positive sound as in the *masker* approach, but also from the noise source itself. This difference can be visualized by the extra arrow presented in Figure 2. In fact, we think the spectro-temporal adaptation of the *Concealer* to the noise source could help provide a more accepted mixture and work with lower added levels.

2.2.2 The concealer signal

In the *concealer* approach, we want the *Concealer* signal c to adapt both on p and s. This adaptation is done temporally and spectrally by operating in the spectro-temporal domain. Since we want that the summation of s and c to be as close as possible to p, one can consider a design rule where M_c is equal to $M_p - M_s$, where M_x is the magnitude of the Short-Term Fourier Transform (STFT) of x. To remove any risk of M_c being negative we further refine the *Concealer* as presented in 1:

$$M_c(t,f) = \begin{cases} M_p(t,f) - M_s(t,f) & \text{if } M_p(t,f) \geq M_s(t,f) \\ 0 & \text{otherwise.} \end{cases} \quad (1)$$

where t and f are respectively the time and frequency indexes of the STFT. The *Concealer* signal c is then obtained by inverse STFT of $C = M_c * e^{i * A_p}$, where A_p is the phase component of the STFT of p.

3. PERCEPTUAL EVALUATION PROTOCOL

Now both *masker* and *concealer* approaches are defined (see Section 2), we want to assess the efficiency of the *concealer* approach as a new way of doing sound masking. A perceptual experiment was conducted, and we hypothesized that *concealer* approach would allow to generate sound mixtures that are perceived as more pleasant than those generated by the *masker* approach.

3.1 Participants

Thirty persons (9 women and 21 men) participated in the experiment. As usual in this kind of preliminary experiment, twenty-one of them have worked at the Institute for Research and Coordination in Acoustics/Music (Ircam, Paris), while nine were recruited from outside Ircam. Their age distribution ranged from 22 to 57 (the median age was 25). A questionnaire addressed at the end of the experiment revealed hearing problems for three participants, including hearing loss beyond 8kHz and tinnitus. Their results were not excluded.

3.2 Stimuli

140 stimuli were generated according to four experimental factors: the approach (2), the source of noise (2), the type of positive sound (5), and the level of the sound mixture between the noise sources and the positive sounds (7).

3.2.1 Choice of the noise source

Two ventilation noises were selected as noise sources. The first is the sound of the ventilation system in an office of the STMS lab at Ircam, and the second was taken from the sound corpus used by Susini et al. in their study on the sound quality of air conditioning noise [14]. This type of sound was chosen for its relevance in the context of shared offices and its stationary behavior, which enabled carrying out some fairly simple first testing with both approaches.

3.2.2 Choice of the positive sound

For the positive sound, some water sounds were selected, as they have already been used in other studies to improve noisy environments (see Cai et al. [13], Radsten Ekman [15], and Radsten Ekman et al. [16]). Five water sounds were chosen for their various spectral content. A fountain sound, a rain sound, a stream sound, a waterfall sound, and waves sound were selected from several sound banks available at Ircam. Although water sounds do not necessarily meet the expectations of shared offices users, it is still interesting to study them to confirm or not their status as positive sounds in this context. In fact, Hongisto et al. [17] investigated the relevance of water-based masking sounds in shared offices, which appeared to be complex.

3.2.3 Choice of mixture level

Instead of using a masking sound-to-noise ratio (MSNR, in dBA) as presented in the study by Cai et al. [13], we defined a parameter named ΔL_{Aeq}, representing the level difference between a mixture and the noise source used for this mixture (in dBA). This indicator allowed us to directly control the level added to the environment, since we wanted to minimize it to be as close as possible to the noise source level. For example, a noise source at 80dBA and a ΔL_{Aeq} at 1dBA impose a mixture generated with this noise source to have its level at 81dBA. For this experiment, seven values of ΔL_{Aeq} from 0 to 3 were chosen in steps of 0.5dBA to generate mixtures that are not louder by more than 3dBA compared to the noise source alone. Furthermore, the noise source level was set to 50dBA, that is quite high for a ventilation noise, but needed to ensure the noise source to be annoying.

3.2.4 Generation of sound mixtures

With all the experimental factors defined, some mixtures were generated between the selected noise sources and positive sounds along both approaches. As mentioned earlier, for the *masker* approach, the *Masker* is set as the positive sound and mixtures are generated by adding each positive sound to each noise source, whereas for the *concealer* approach, the *Concealer* is first computed following the steps detailed in Section 2.2.2, and then added to the noise source to generate a mixture. For each mixture, the noise source was set to 50dBA, so the level of the mixtures was included between 50 and 53dBA.

3.3 Procedure

The experiment took place in an audiometric booth in the laboratory. Participants were presented the 140 stimuli through headphones, as realistic reproduction was not identified as a principal experimental factor for this exploratory study. Meanwhile, headphones ensured a good degree of immersion into the stimuli. A Best-Worst Scaling paradigm was chosen to assess this large set of stimuli, and the Value Learning algorithm was used to score all stimuli (convergence of the algorithm was verified and reached around 95% for 30 participants [18]). Such method consists in asking participants to evaluate stimuli in random groups of 4 by selecting the most pleasant stimulus and the least pleasant one. To do so, an instruction was given to encourage participants to project themselves into an environment that they frequently use (their work environment, for instance). Each stimulus had to be considered as part of the general sound atmosphere of this environment. A score was calculated for each stimulus on the basis of all participants' judgments. At the end of the rating phase, participants did a recognition task with the five positives presented in random order. After the experiment, a questionnaire was presented to participants with questions about their personal information (name, email address, age, gender, job and possible hearing problems), their noise sensitivity, and their work environment.

3.4 Analysis

Pleasantness scores were computed for all the stimuli from participants' judgments. To study the effect of the approaches (masker and concealer) on the scores, a first T-test was used to compare the average scores for both approaches. Then, this comparison was made on smaller samples by computing T-tests between the average scores for both approaches according to the other experimental factors. This provided a clearer picture of the difference between the two approaches. Linear regressions were also computed for each water sound used in the mixtures.

4. RESULTS

4.1 Effect of masking strategy on pleasantness scores

Figure 3 shows the pleasantness scores obtained by the mixtures generated with each approach. Although the difference between the two approaches is not statistically significant (p-value=0.07), the *masker* approach appears to provide better results than the *concealer* approach. However, this result could not be confirmed by looking at the difference between both approaches for specific experimental factors. For instance, p-values ranged from 0.2 to 0.7 were found for the added level factor (Figure 4).

4.2 Effect of added level on pleasantness scores

The results brought to light some effects of different experimental factors on pleasantness. The most important effect on participants judgments is that of the added level.

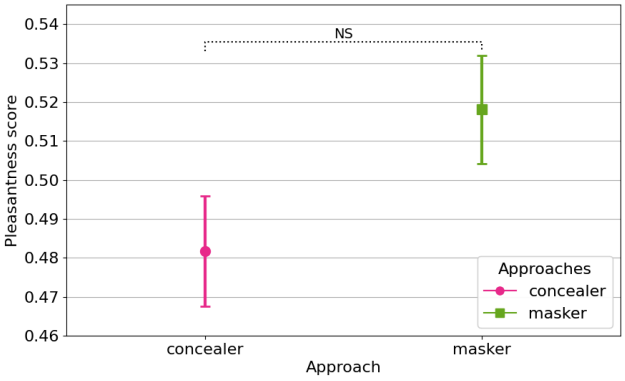


Figure 3. Average pleasantness scores of mixtures depending on the approach used (*concealer* in circle and *masker* in square). The obtained p-value was $p = 0.07$.

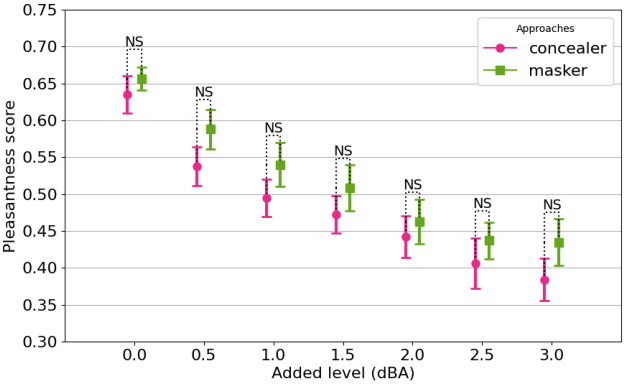


Figure 4. Average pleasantness scores of mixtures depending on the added level (ΔL_{Aeq}) and the approach used (*concealer* in circle and *masker* in square). The obtained p-values were $0.2 < p < 0.7$.

Figure 4 shows the relationship between mixtures' pleasantness scores and the added level, which seems to be almost linear. In fact, the pleasantness scores of the mixtures decrease with the added level increase, inducing the pleasantness judgments get worse, whatever the approach, the noise source or the positive sound used. This can be explained by the fact that the selected ventilation noises are not a posteriori really annoying. Indeed, despite the fact that we artificially emphasized their level (see Section 3.2.3), the added level is not appreciated.

4.3 Effect of water sounds masking component on pleasantness scores

The second effect that appear is that of the type of positive sounds. Indeed, from the full lines in Figure 5 we can see that the perception of mixtures depends on the type of water sound used. The pleasantness rating is ordered in the following sequence: stream $>$ waves $>$ rain $>$ fountain $>$ waterfall, meaning the pleasantness scores strongly depend on the subjective feeling of the water sounds. However, as the added level is the level of the water sound included in the mixtures, the level effect can be reinterpreted. In fact, Figure 5 shows that the less the water sounds are perceived, the more pleasant the mixtures are rated by the

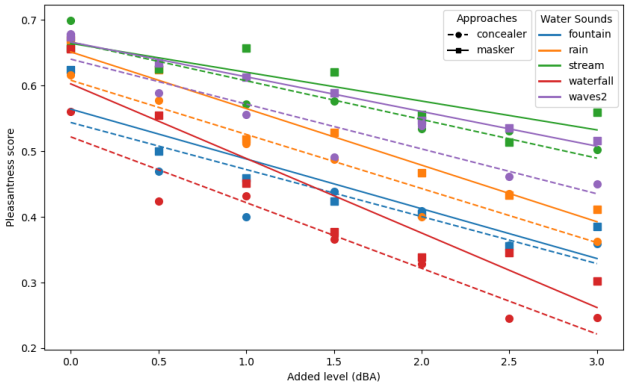


Figure 5. Pleasantness scores of mixtures depending on the added level (ΔL_{Aeq}), the approach (circles and squares) and the positive sound used (colors)

participants. Thus, the addition of water sounds throughout both *masker* and *concealer* approaches has an effect on pleasantness scores, but it is not a positive effect as it could not counteract the level effect. As for the ventilation noises, water sounds may not be as pleasant as we thought, especially considering a work context.

5. DISCUSSION

The pleasantness scores of the mixtures decrease with the perception of water sounds added to the ventilation noises. These results questioned our hypotheses.

First, ventilation noises are assumed to be annoying, but they might not actually be so in the context of the experiment, maybe due to their stationary behavior which makes them more accepted than other sounds with irregular temporal and spectral structures.

Second, water sounds are assumed to be pleasant. However, some participants expressed their discomfort about the water sounds at the end of the experiment. This does not confirm the literature on the relevance of water sounds in acoustic environments quality enhancement [15, 16]. In particular, the effect of water sounds on pleasantness did not counteract the level effect, as in Cai et al.'s study where water sounds helped reducing annoyance when added to an industrial noise [13]. Therefore, lower levels should be considered to study the efficiency of the *concealer* approach. However, the results join some research in open-plan office contexts that draw controversial conclusions about their use as masking sounds [17].

Third, the source level was set to generate mixtures between 50 and 53dBA, but additional levels are found to be consistently badly perceived, highlighting the important effect of loudness on the pleasantness judgments, as largely demonstrated in the literature [19]. Indeed, Chevret and Lenne showed masking sound levels above 45dBA are considered too loud in open-plan offices [20].

Finally, one limitation of this study is that we do not use any control condition to assess the pleasantness of both ventilation noises alone. Further studies should include some references to be able to conclude on the masking effect of the different approaches. Furthermore, our strong hypotheses about the choice of the noise sources and the

water sounds, as well as the way the *concealer* signals were constructed, could partly explain the lack of statistical significance of the results. To further this research on the *concealer* approach, we first plan to gain a better understanding of people sound-related experiences at work through a field study (see [21]). In addition, a collaboration with a group of composers and sound designers has been initiated to be more accurate in the design of the *concealer* signal.

6. CONCLUSION

The aim of this experiment is to explore the efficiency of a masking approach named *concealer*, which is an original approach based on a minimal added loudness paradigm. Its relevance is investigated by comparing it to a traditional sound masking approach, named *masker*. To assess whether the *concealer* approach could provide better results in improving a specific noise source than *masker* approach, sound mixtures are generated along both approaches. Two ventilation noises are selected as noise sources and five water sounds as pleasant masking sounds. Sound mixtures are evaluated for their pleasantness, and the results do not show any significant difference between both approaches. Even if we could not conclude about the relevance of the *concealer* approach in the experiment context, some effects of the different experimental factors on pleasantness could be observed, that raise some important questions for further research. Especially, as adding water sounds to the ventilation noises is badly perceived, we need to reconsider the choice of annoying and pleasant sounds to be used to create the sound mixtures.

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