ICBEN 2017
18 – 22 JUNE
ZURICH

12th ICBEN Congress on
Noise as a Public Health Problem

The bigger the better and the more the merrier? Realistic office reverberation levels abolish cognitive distraction by multiple-voice speech

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ABSTRACT

Background speech is consistently rated as the most objectionable noise in open-plan offices. There is ample evidence that acoustic variation in the speech is a key determinant of its disruption of cognitive performance. Theoretically, any means of attenuating sound variability such as increasing room reverberation should help counter the negative impact of irrelevant speech. To date, such benefits have been reported only with reverberation times uncharacteristic of office environments. Based on the observation that multiple voices are less disruptive than a single voice, we sought to test the joint impact of number of voices and reverberation on the disruptive effects of speech. The effects on a (visually-presented) short-term serial recall task of adding realistic reverberation times (0.4 or 1 s) to irrelevant speech emanating from either 3 or 15 superimposed voices was compared to a quiet control condition. Disruption diminished with both an increase in number of voices and with increasing reverberation and disappeared in the 15-voice+long-reverberation condition, suggesting that realistic room reverberation levels may ameliorate the damaging effects of background speech in relatively large multiple-occupancy offices.

INTRODUCTION

Background noise is a fundamental problem within workplace environments. It is associated with a decrease in productivity [1], motivation [2], satisfaction [3], and well-being [4], all of which can confer substantial costs for organizations [5]. In 2015, a survey showed that 80% of office workers reported being regularly disrupted by office noise [6]. Respondents also claimed that their productivity could drop (by up to 66% on average) in a noisy environment. Despite the wealth of evidence suggesting that noisy environments are damaging, the open-plan office solution is often favoured [7]. Within such a setting, background speech is consistently rated as the most objectionable noise [8]. Yet, the ubiquity of conversations in the workplace—between coworkers or over the telephone—means that workers are inescapably exposed to extraneous speech. This considerable amount of exposure to others' conversation has become a central concern in the modern work environment given that irrelevant speech, beyond its annoying quality, is also known for its adverse consequences for cognitive functioning [9-10]. One solution often implemented within the office setting to reduce the disruptive impact of irrelevant speech on cognition is the introduction of masking sounds. While such an intervention can be quite effective, it can prove costly. More importantly, the addition of (masking) noise to the auditory environment is not generally appreciated by office workers [11]. Moving away from the installation of noise-emitting devices, the present study sought to explore the environmental characteristics of an office setting itself that might influence the disruptive power of speech, which could in turn suggest practical recommendations.

Research on auditory distraction has demonstrated that the process of encoding and maintaining the temporal order of events is particularly vulnerable to disruption by background speech (see [12] for a review). There is ample evidence that tasks representative of the type of work typically undertaken in office environments where seriation is a likely component, such as proofreading [13], writing [14], reading comprehension [15], and mental arithmetic [16], are impaired by the mere presence of speech. In the laboratory, the *irrelevant sound effect* (ISE) is usually studied using a short-term serial recall task in which participants must recall the order of visually presented stimuli such as letters or digits. It has been shown that the meaning of the sound plays little, if any, role in the disruption of serial recall. Indeed, the ISE not specific to speech [17]. Instead, the key characteristic underpinning the disruption is the presence of acoustic variation within the sound. For instance, a changing-state sequence such as 'g, h, r, x, s …' is more disruptive than a steady-state sequence such as 'g, g, g, g, g …' which produces little, if any, disruption compared to quiet. This *changing-state effect* is best explained by a conflict of two similar processes involving the processing of the order of events. According to the interference-by-process account [10, 17-18], the obligatory segmentation and perception of changes in a sound sequence—a by-product of auditory streaming processes (see [19])—yields information about order, which interferes with the deliberate serial ordering process supporting the reproduction of the to-be-remembered list. Such automatic order encoding is minimal or absent with a steady-state item.

The fact that changing-state sound is far more disruptive than steady-state sound has implications for noise abatement: Any factor that reduces the degree of acoustic change should diminish auditory distraction. This is why the introduction of masking noise tends to be effective in reducing the detrimental effects of background speech: The addition of continuous noise masks the various pitch and loudness changes in the speech signal, therefore diminishing the number of cues to segmentation and hence the perception of change between successive elements [20]. Interestingly, similar attenuating effects are obtained by increasing the number of competing voices within the speech [20-21]. This *babble effect* is attributable to the fact that adding voices increases the tendency for troughs in the signal produced by one voice—which would typically act as segmentation cues—being 'filled in' by peaks in another, thereby reducing the degree of variability in the overall acoustic signal.

Based on the same reasoning, it would be expected that increasing reverberation within offices should also help to reduce the ISE. Indeed, the multiple reflections of a signal bouncing back from surfaces should affect the degree of acoustical variation in a similar manner to that of multiple voices, that is, by blurring the boundaries between successive utterances and therefore attenuating the perception of acoustic change within the irrelevant speech. Although the changing-state hypothesis predicts that highly reverberant environments should reduce the effect of irrelevant speech compared to environments with shorter reverberation times, the current ideology conveyed by manufacturers in the noise reduction industry goes in the opposite way by promoting the use of acoustic tiles that absorb rather than reflect the sound in order to reduce reverberation. The prediction that reverberation should reduce the ISE is supported by Beaman and Holt [22] who showed that with a reverberation time of 5 s, changing-state irrelevant speech was stripped of its disruptive effect. However, as pointed out by Perham, Banbury, and Jones [23], a reverberation time of this length is more representative of that heard in large auditoriums than in open-plan office environments in which reverberation times typically range between 0.4 and 1 s. When using realistic office reverberation times (specifically, 0.7 and 0.9 s), Perham and colleagues failed to observe any beneficial effect of reverberation on the degree of auditory distraction, at least relative to quiet (no control sound condition without reverberation was included).

Whereas the findings of Beaman and Holt [22] demonstrate the shielding effect of reverberation against the ISE, those of Perham and colleagues [23] cast doubt on the applicability of this factor to workplace environments as a potential solution to the negative impact of extraneous speech on cognition. A limitation of both of these studies, however, is that the irrelevant speech was conveyed by a single talker. In large multiple-occupancy offices, background speech will rarely consist of a single voice. In such work environments, it is more common to hear multiple concurrent voices. Given that multiple voices tend to be less disruptive than a single voice by virtue of their smoothing effect on acoustical variability (e.g., [20]), it is possible that the distraction-reducing power of realistic levels of reverberation has been underestimated.

With the aim of examining whether reverberation can help shield against auditory distraction under realistic office noise conditions, the present study examined the joint impact of number of voices and reverberation on the disruptive effects of background speech on cognitive performance. In the context of the irrelevant sound paradigm, participants performed a visual serial recall task while ignoring extraneous speech. The effects on recall of adding realistic reverberation times (0.4 or 1 s) to irrelevant speech composed of either 3 or 15 superimposed voices was compared to a quiet control condition. We predicted that with such multiple-voice background speech, the addition of reverberation levels characteristic of office environments will decrease the disruptive impact of that speech (cf. [23]).

METHOD

Participants

Twenty-eight adults (12 men), ranging from 19 to 48 years of age (*M* = 27 years) took part in the experiment in exchange for a small honorarium. All volunteers reported normal or corrected-to-normal vision and normal hearing.

Materials

The to-be-remembered visually presented sequences comprised eight digits randomly selected without replacement from the set 1-9 and arranged in a quasi-random order with the constraint that successive digits were not adjacent integers (see Figure 1). Each item was approximately 2.5 cm in height and presented sequentially in Times New Roman font at the center of the screen located at approximately 60 cm from the participant. Each digit was presented for 750 ms and the interstimulus interval (offset to onset) was 250 ms.

To create background speech, 15 people (6 men) were individually allocated a script to recite and were instructed to sound natural. Scripts were company profiles of over 200 words that were randomly selected from a graduate recruitment website. Voices were recorded and edited using SoundForge software (Sony) in a sound-attenuated recording booth. A sample of 20 s was chosen from each recording on the basis of sound quality and speech continuity. The first 4 s and the last 2 s of each sample were faded in and out, respectively. Speech samples were randomly combined to form five files that each contained three superimposed voices. All original files were combined to create a file containing 15 superimposed voices. Sound files were presented through stereophonic headphones at approximately 65 dB(A).

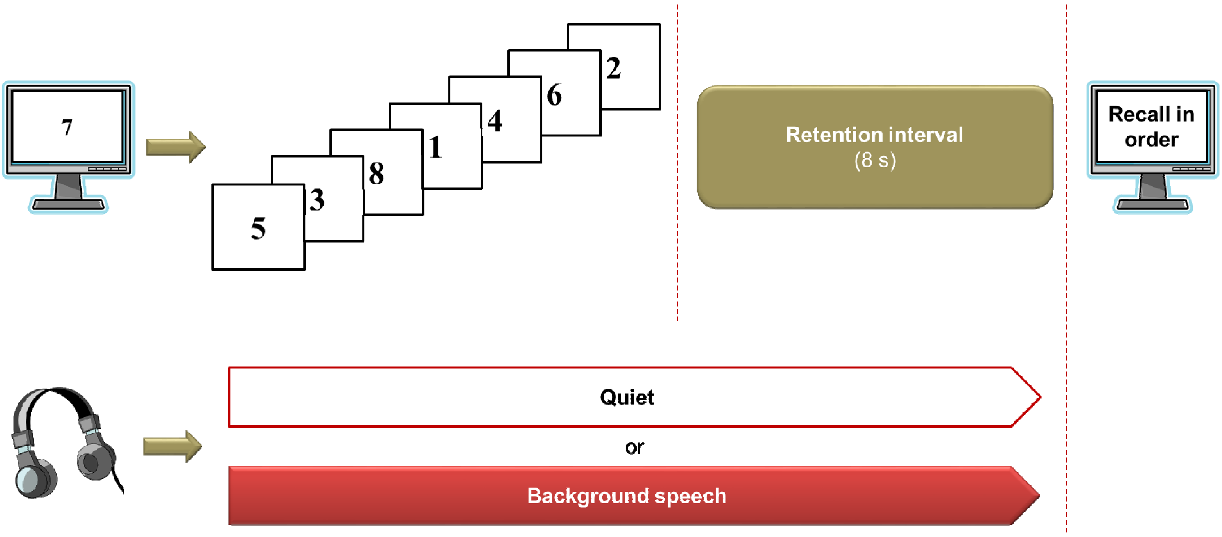

Figure 1: Schematic diagram of the paradigm used: (Top) Representation of the sequential display of the visual list followed by an 8-s retention interval and then the response phase. (Bottom) When present, background speech was presented throughout the presentation and retention phases.

Reverberation treatment was added to the audio files containing either 3 or 15 superimposed voices. Specialist software was used to create a simulation of realistic office reverberation (see [24]). The room was an estimation of the minimum-size room required for a situation in which 15 concurrent voices might be heard. The minimal amount of floor space per person in the UK is 6 m² (IFMA, 2007). If we assume concurrent speaking by approximately half the occupants at any given time, with a little additional space for movement, a minimal room size for 15 concurrent voices would be 200 m². Reverberation time was calculated using a room size of 20 m × 10 m × 3 m. If the origin is the bottom left corner of the room, the sound source was placed at 15 m × 5 m × 1.5 m. The ‘listener’s’ head was plotted at 5 m × 5 m × 1.5 m, with 18 cm between the two ears (left ear at 5.09 m along the width of the room and right ear at 4.91 m). Absorption level was calculated using Sabine’s formula; it was frequency independent and equal on all surfaces of the room. Office reverberation typically ranges from 0.4 to 1 s [23]. The long reverberation time was set at 0.98 s, which had an absorption coefficient of 0.17 and a direct-to-reverberant ratio of –15.72 dB. The short reverberation time was 0.4 s, which had an absorption coefficient of 0.42 and a direct-to-reverberant ratio of –8.87 dB. Reverberation increased sound intensity so conditions were all normalized. Reverberation only affects sound after a delay so 0.2 s of original sound was removed from the start of the reverberation files. Reverberation files were shortened so that all samples were 20 s long. Fade ramps were not adjusted. The onset and offset of the sound was not sudden as the maximum intensity at either end of the files was still below 0 dB.

Design and procedure

The design comprised two within-subject factors: reverberation (none, low level, high level) and number of voices (3, 15). A seventh condition of quiet was included as a control. Following two practice trials in quiet, participants performed 12 trials in each condition for a total of 84 experimental trials. Trials were quasi-randomized to ensure that no condition was repeated on consecutive trials. Participants received a break of 5 min after 42 trials.

Participants were tested individually in a sound-attenuated booth. They read standard instructions informing them of what the serial recall task involved (the recall of the eight digits in their order of presentation) and asking them to ignore any sounds presented over the headphones. They were not told about the characteristics (content, number of voices, reverberation) of the irrelevant sound. As illustrated in Figure 1, on each trial, a sequence of digits was presented visually (presentation phase) followed by an 8-s retention interval (retention phase). The to-be-remembered list was always accompanied by an irrelevant auditory sequence, except in the quiet condition in which no sound was presented. When present, the sound was played until the end of the retention interval. Participants were informed that the trials would be presented at a preset pace: At the end of the retention interval, the word ‘recall’ appeared on the screen which signaled to participants that they had 15 s to write out the to-be-remembered list. A 500-ms tone was presented over the headphones after 13 s of the response phase to warn participants that the presentation of the first item of the next sequence was imminent.

RESULTS

The raw data were scored according to the strict serial recall criterion: To be recorded as correct, an item had to be recalled in its original presentation position. Figure 2 presents the percentage of items correctly recalled in the seven conditions of the experiment. It is evident that serial recall performance was a positive function of the number of voices and the level of reverberation in the irrelevant speech. We begin by assessing the impact of these two factors in a 2 (number of voices) × 3 (reverberation) repeated-measures ANOVA. The analysis revealed a significant effect of number of voices, $F(1, 27) = 21.435$, $p < .001$, confirming that recall was better with 15 than 3 background voices. The effect of reverberation was also significant, $F(2, 54) = 13.257$, $p < .001$. Multiple comparison tests showed that performance was better with low than no reverberation, $F(1, 27) = 9.323$, $p = .006$, and with high than low reverberation, $F(1, 27) = 4.780$, $p = .039$. A significant two-way interaction was also found, $F(2, 54) = 3.164$, $p = .006$, reflecting the fact that reverberation had a greater effect on the speech condition containing more acoustical variation, that is, the 3-voices condition.

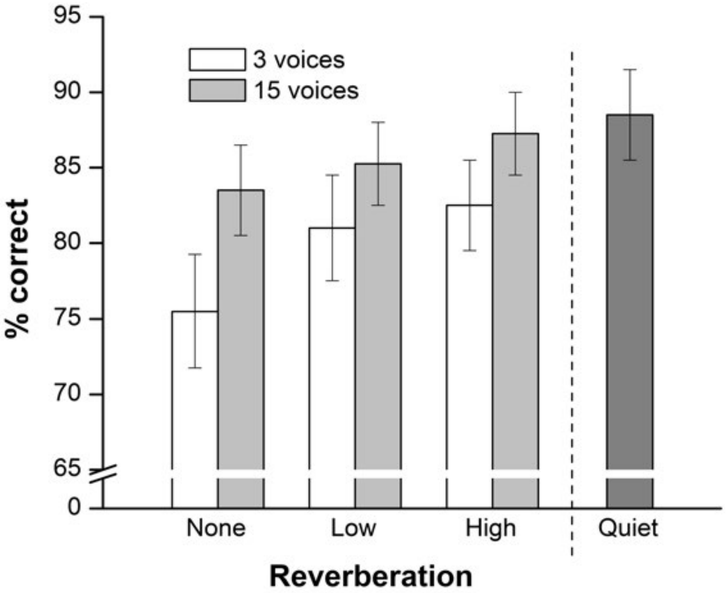

Figure 2: Mean percentage of items correctly recalled in the quiet condition and in the six conditions of background speech. Error bars represent the standard error of the mean.

Second, we contrasted recall performance in each sound condition to that in the quiet condition. As shown in Table 1, these planned contrasts revealed that performance in all sound conditions differed significantly from that in quiet, apart from the 15 voices with high reverberation condition. Thus, the combination of a large number of concurrent voices with the higher reverberation level eliminated disruption by irrelevant speech.

Table 1: Planned contrasts on recall performance for all sound conditions vs. quiet

Sound condition	***F*(1, 27)**	***p***
No reverberation – 3 voices	40.910	< .001
No reverberation – 15 voices	12.653	.002
Low reverberation – 3 voices	21.006	< .001
Low reverberation – 15 voices	10.558	.004
High reverberation – 3 voices	17.157	< .001
High reverberation – 15 voices	1.918	.179

DISCUSSION

The present study examined the joint impact of multiple voices and large office-like reverberation on cognitive distraction by background speech. The results showed that serial recall performance improved with an increase in both the number of voices in the background (cf. [20-21]) and the level of reverberation (cf. [22-23]). Strikingly, disruption was eradicated when the irrelevant speech was composed of 15 superimposed voices with a reverberation time of about 1 s. These findings demonstrate that the combination of multiple voices and a high (but still realistic) level of reverberation can prevent the disruptive impact of irrelevant speech. Such a pattern of results is consistent with the changing-state hypothesis in which the extent of auditory distraction is a function of the degree of acoustic change within the sound [17-18]. With regard to the impact on the perception of the irrelevant speech, multiple voices and reverberation share the same modus operandi: Both factors act to ‘smooth out’ the signal, attenuating cues to segmentation and the degree and number of perceptible changes. When exploited in combination, it seems these factors could be a powerful tool for counteracting the adverse effects of background speech on cognition.

Previous research had shown that reverberation reduces the negative impact of extraneous speech but only with very long reverberation times uncharacteristic of office environments [22-23]. Yet, these studies used speech generated by a single talker. The present study established that in an environment with multiple talkers—a context more representative of open-plan offices—even realistic office-like reverberation markedly decreases the disruptive impact of background speech. Such a conclusion has important implications for office noise abatement as it argues against the popular idea that it is always beneficial to reduce the level of reverberation within the workplace environment in order to optimize cognitive efficiency. Accordingly, the process of lowering the level of reverberation through installation of acoustically treated ceilings and wall panels may not be an appropriate way to fight against office noise pollution; quite the opposite. The present findings suggest, counterintuitively perhaps, that if an office is to be multiple-occupancy, then increasing the number of co-workers (see also [20]) and greater (realistic) room reverberation may ameliorate the damaging effects of background speech on workplace productivity.

One consequence of reducing the acoustic variability of the speech stream is the diminution of speech intelligibility [20]. Given that meaningful background speech is also known for its disruptive effect on language-based tasks such as writing (see [25] for a review), making the extraction of the meaning from speech signal more difficult for the cognitive system can further help mitigate against the distraction produced by irrelevant speech. Indeed, previous work has demonstrated that reducing the intelligibility of the speech via masking reduces the disruption it produces to tasks underpinned by semantic processes [5, 20, 26]. Another desirable outcome of reducing speech intelligibility is an increase of privacy. The other side of this coin, however, is that reduced intelligibility will also impair the comprehension of task-*relevant* speech, making conversation between co-workers within the office more difficult. Therefore, the combination of a relatively large number of people and a realistically high reverberation level may help to protect cognitive functioning and increase privacy but at the cost of impaired communication. Workplace satisfaction depends on a delicate balance between speech privacy and intelligibility [27] and solutions designed to satisfy both communication and privacy demands may be difficult to achieve. Given the promising benefits highlighted in the present study of adding office-like reverberation to multiple-voice background speech, further research should look more closely at the effects of reverberation in large multiple-occupancy offices.

There are limitations to the application of the present findings to the workplace. Increasing reverberation can produce an increase in the intensity of the sound within the office environment, similar to the addition of a masking noise, which can be unpleasant. For instance, Perham and colleagues [23] reported that participants rated the longer reverberation time (0.9 s) more annoying and distracting than the shorter reverberation time (0.7 s) even though neither condition was more disruptive than the other. Such an effect on intensity is of particular importance in the context of multiple voices, where each additional voice will also increase the intensity level of the irrelevant speech. Yet, in the present experiment, sound intensity was normalized across speech conditions. Although future research on the impact of reverberation on auditory distraction should take the potential effects of reverberation and multiplicity of voices on noise intensity into account, it is worth noting that the intensity of the sound does not play a role in the ISE [28-29].

Another limitation of the present study is that the voices (regardless of condition) all emanated from the same spatial location, which of course is unrealistic (see also [20]). Jones and Macken [21] showed that while increasing the number of voices within the irrelevant speech diminishes auditory disruption, the disruption is reinstated if each voice is allocated to a different spatial location. It is thus possible that spatially separating the voices in the conditions of the present experiment would have altered the results. However, the effect of spatial separation was found by Jones and Macken using auditory sequences composed of six different voices, far fewer than the 15 superimposed voices included in the present study. With this many voices, spatial separation may not have had that much effect: Even if all 15 voices were allocated to a different azimuthal position around the ‘listener’s’ head, the amount of physical separation between some of the voices would necessarily be modest such that perceptual separation may also be relatively weak (see, e.g., [30]). Indeed, in a shared office with 15 talkers, the probability of one voice emanating from the same or similar direction to another (i.e., one talker’s speech coming from behind that of another) is much higher than with only six talkers. Moreover, the identification of a sound’s spatial source or direction tends to be impaired with reverberation [31]. Nevertheless, future research should ascertain the moderating effect of spatial separation on the critical number of concurrent voices in combination with reverberation on the disruption of cognitive performance by irrelevant speech.

CONCLUSION

The present study shows that factors intrinsic to open-plan offices such as the number of concurrently audible voices and reverberation level can modify the extent of auditory distraction observed in such environments. Given that the combination of multiple talkers and realistic office reverberation ameliorates the adverse effects of background speech on cognition, it is possible that companies could save on investment in noise-emitting devices and acoustic treatments by considering the reverberatory properties of an office space in combination with the number and spatial organization of co-workers within that space.

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