Auditory distraction in open-plan study environments

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Auditory distraction in open-plan study environments: Effects of background speech and reverberation time on a collaboration task

Ella Braat-Eggen, Marijke Keus v.d. Poll, Maarten Hornikx, Armin Kohlrausch

Avans University of Applied Sciences, Tilburg, the Netherlands
Eindhoven University of Technology, the Netherlands
University of Gävle, Sweden

Abstract

Previous research has shown that semantic-based tasks are negatively influenced by semantic aspects in background speech. Collaboration is an important task in open-plan study environments and is a semantic task which might be disrupted by background speech. Therefore, the aim of this study was to analyze the influence of irrelevant background speech on student-collaboration.

Participants worked in pairs to solve spot-the-difference puzzles, by using the ‘DiapixUK’ collaboration task, while they were exposed to different background sound scenarios. The composed sound scenarios varied in semantic content (mother tongue and foreign language background speech) and reverberation time (short vs long), the latter affecting speech intelligibility.

Although a longer reverberation time decreases the intelligibility of background speech and a foreign language decreases meaningfulness of speech, no significant changes in performance were found. On the other hand, the data show an increased perceived disturbance for a longer reverberation time, which we interpret as an increased difficulty of interpersonal communication in the collaboration task due to the increased level of the background speech. The quiet reference condition was the most preferred sound condition which is in line with both the effect of a low background sound level and the absence of semantic interference.

1. Introduction

An acoustic environment should support people doing their tasks without being disturbed and causing loss of performance. Unfortunately, it is known that auditory distraction is a major problem in all kinds of open-plan work environments [1–4]. For instance, many studies show the detrimental effect of background speech on performance of semantic tasks such as comprehensive reading [5,6], proof reading [7–10] and writing [11,12]. Unfortunately, background speech is common in an open-plan work environment due to telephone calls and interactions between workers [2–4]. These interactions might, in the best case, lead to communication and collaboration. On the other hand, collaboration is also a semantic task which might be disrupted by background speech.

The importance of collaboration tasks in open work spaces is significant for open-plan study environments [3]. Due to new ways of learning, informal learning places (e.g. libraries, study areas, lobbies, atria etc.) become more and more important [13,14]. Not only classrooms and lecture halls suitable for teacher-centered instructions but also work environments for participatory learning, group work and individual work are needed [14,15]. Especially spaces intended and designed to accommodate individual as well as small group activities of students, so called open-plan study environments [3], have to support a diversity of tasks in the same environment. A situation of several groups working on their group assignment in the same open-plan study environment is a very common situation.

This so called collaborative learning can be defined as 'working in a group of two or more to achieve a common goal, while respecting each individual’s contribution to the whole’ [16]. Collaboration therefore implies interaction among students to produce a common product and involves negotiations, discussions, and integrating others’ perspectives [17]. Verbal communication is a crucial element of all those activities and will imply speech production. Therefore, background speech, due to speech production of other working groups in the same environment, is unavoidable and all students working in an open-plan study environment will more or less be influenced by background speech while doing their tasks. Therefore, the focus in the present study was on the influence of...
background speech on a collaboration task in an open-plan study environment.

1.1. Why is background speech disruptive for cognitive performance?

The characteristics of a sound in combination with the characteristics of a cognitive task can predict whether the sound will impair cognitive performance in the task [18–20]. The “Duplex-Mechanism Account of Auditory Distraction” (DMAAD) [21,22] describes two mechanisms through which sound can disrupt cognitive performance: attention distraction and specific interferences.

The first mechanism, attention distraction, gives an explanation of why an unexpected signal can disrupt performance (attentional capture). Sudden or abrupt changes in the signal capture attention and draw it away from the focal task towards the background sound signal [23]. For instance, a signal like ‘B B B B B’ is not distracting, while the ‘K’ in the series ‘B B B K B B B’ is distracting and decreases performance because of the violation of the expectation for another ‘B’ (i.e. the deviation effect) [21–24]. Besides an unexpected change in the sound signal, also other aspects in the sound can capture attention and thereby disrupt performance, like hearing one’s own name in a background conversation [25], or hearing other interesting or relevant information [22,23,26,27,28,29].

The second mechanism mentioned in the DMAAD to explain why background sound can disrupt cognitive performance is the occurrence of interference between similar cognitive processes (interference-by-process). A classical way of studying this is measuring serial recall performance. In serial recall, a person has to recall a series of visually presented items (e.g. numbers, words or letters) in the correct serial order. Task-irrelevant sound that is played during the presentation of the visual stimuli impairs task performance. The magnitude of the impairment depends on the acoustical variability of the sound [30,31]. A background sound consisting of almost no acoustical variability, like ‘B B B B B B B’ (a steady state signal) is almost not disruptive for the serial recall performance. Performance in a background with a steady state signal is similar to performance in quiet. On the other side, a signal with acoustical variability, like ‘B X K C M L’ (a changing state signal) impairs serial recall performance [32–35]. This changing state effect [35] can be explained as an interference between voluntary processes required to recall the serial order of the visually presented items and similar automatic processes required to analyse the serial order of the items in the automatically incoming auditory signal, i.e. interference-by-process [23,36]. For instance music and speech can disrupt cognitive performance as long as there is acoustical variability in the sound signal [35,37].

A property that distinguishes speech from other sounds is that speech not only has acoustic characteristics, like changes in frequency and amplitude of the signal, but also has semantic characteristics, like the words and sentences that contain meaning [38]. In line with the interference-by-process account, an interference also occurs between semantic cognitive processes used to automatically analyse the meaning in the background speech signal and similar semantic cognitive processes involved in the execution of a semantic based task, like reading and writing [19]. This should mean that speech intelligibility and meaningfulness of the background speech signal predict distraction on semantic tasks like reading and writing. As highly intelligible background speech contains more semantic information compared to a less intelligible signal, a highly intelligible signal should be more disruptive. Further, a highly intelligible speech signal will reasonably contain more relevant or interesting information that can capture attention and, as explained by the framework of attentional capture, disrupt performance more than a less intelligible signal. Research indeed shows that an increase of intelligibility [8,12,39,40] and meaningfulness [5–7,11,19] of the background speech is related to an increase of disturbance and a decrease of performance on a semantic task.

As mentioned earlier, a serial recall task is also disrupted by background speech, although not due to its semantic properties but due to its auditory-perceptive characteristics [41]. Therefore, a serial recall task is as much disturbed by background speech in an unknown foreign language as by background speech in the mother language [19]. Nevertheless, for tasks with semantic characteristics, the semantics of a speech signal are decisive [41]. Since collaboration has semantic characteristics, in the current study, we expected a highly intelligible and meaningful background speech to be more disruptive compared to less intelligible and less meaningful background speech.

1.2. Individual differences

Another factor – in addition to the characteristics of the sound and the cognitive task – that can influence how an individual reacts to noise, is individual differences, like noise sensitivity. Individual differences are important to take into account when organizing workplaces, as those individual differences might require different work environments. It is reasonable to argue that individuals that are sensitive to noise will be more distracted by noise when undertaking a cognitive task, and as a consequence perform worse compared to their less sensitive colleagues. However, studies that investigated the relationship between subjective noise sensitivity (i.e. noise sensitivity measured by self-rating) and cognitive performance have only found small correlations or no correlations at all [42–45]. In those studies, though, background sound consisted of different kinds of noise, or unintelligible speech. None of the studies used intelligible background speech. Neither has the correlation between noise sensitivity and performance on a verbal collaboration task been investigated. In a recent field study in open-plan study environments [3], noise sensitivity of students showed to be related to the disturbance by noise. Therefore, in the current study we investigated whether individual differences in subjective noise sensitivity predict individual differences in susceptibility to the effects of background speech on collaboration.

1.3. How to influence speech intelligibility and meaningfulness?

Room acoustics will influence the intelligibility of speech. A widely used parameter to measure or describe speech intelligibility between a speaker and listener is the speech transmission index (STI), where a value of 1 indicates an excellent speech intelligibility and a STI value below 0.3 indicates nearly unintelligible speech. The most important aspects that will influence speech intelligibility in an environment are the speech level relative to the background noise level at the listeners’ position and the reverberation time [46].

A long reverberation time will decrease speech intelligibility due to the effect of smoothening the temporal profile of the waveform [46,47]. On the other hand, the level of speech at the listeners’ position is of great importance, a high speech to noise ratio will result in more intelligible speech. The speech level in a room will decrease over distance between talker and listener due to sound absorbing materials in an environment. If more sound absorbing materials are applied to walls, ceiling and floor, not only the intelligibility will increase due to a shorter reverberation time but also the speech level will be reduced at the listeners’ position and the reverberation time [46].

A low reverberation time will decrease speech intelligibility due to the effect of smoothening the temporal profile of the waveform [46,47]. On the other hand, the level of speech at the listeners’ position is of great importance, a high speech to noise ratio will result in more intelligible speech. The speech level in a room will decrease over distance between talker and listener due to sound absorbing materials in an environment. If more sound absorbing materials are applied to walls, ceiling and floor, not only the intelligibility will increase due to a shorter reverberation time but also the speech level will be reduced at the listeners’ position resulting in a decrease of the intelligibility. Speech related room acoustic parameters as described in ISO 3382-3 [48], like spatial decay rate of speech (D2,5) and sound pressure level of speech at 4 m (Lp,A,5m) are correlated with intelligibility. A decrease of the speech level over distance, expressed in a higher D2,5 or lower Lp,A,5m value,
will result in a decrease of the speech to noise ratio and will therefore lower speech intelligibility. Reducing the speech level over distance can not only be accomplished by applying more acoustic absorbing materials but also by installing high sound screens in an open environment [49,50].

The background noise level will also influence the intelligibility of a speech signal because it reduces the signal to noise ratio, therefore, if the background noise increases, speech intelligibility decreases. In a multi-speaker background situation, the noise consists of speech and the loudest background voice is most intelligible for a person doing a task. Also in this situation an increase of the background speech will lead to a reduction of the intelligibility of the speech of the loudest speaker.

A special situation occurs if the task of a worker requires verbal communication, as in a collaboration task. An increase of the background noise level will lead to a louder speech level of the communicating participants in order to compensate the decrease of the signal to noise ratio between them. This increase of the speech level will implicate a higher background noise level for other workers in the environment. The latter effect is called the Lombard effect [51], a well-known phenomenon that people in a room speak at a higher sound level due to the background speech, which again leads to a higher background speech level. The Lombard effect was found to start at around an ambient noise level around 45 dB and a speech level of 55 dB [52].

A poorly intelligible speech signal can also be less meaningful for the listener, after all, unintelligible speech is also meaningless. It should be noted that meaningless speech is not the same as irrelevant speech, because irrelevant speech can still have a meaning. In an experimental setting meaningfulness of speech can be influenced by for instance spectrally-rotating the speech [11], by playing sentences in reverse [6,7] or by the language of the speech [7]. Research has shown that background speech in an unknown foreign language will decrease the disturbance and increase the performance of a semantic task compared to background speech in the mother tongue [7,40].

1.4. The aim of the study

To the authors’ best knowledge, the influence of background speech on the perceived disturbance and performance of a collaboration task has not been previously investigated. Because of the importance of this task in an open-plan study environment, the aim of this study is to analyze the influence of background speech on the perceived disturbance and performance on a collaboration task considering intelligibility and meaningfulness of the background speech.

The hypothesis is that an increase of intelligibility and meaningfulness of the irrelevant background speech will lead to an increase of disturbance and a decrease of performance in the collaboration task. Furthermore, noise sensitivity will be taken into account in this study. The hypothesis is that highly sensitive individuals will be more disturbed by the background speech and will show a decrease of performance in the collaboration task compared to less sensitive individuals.

2. Materials and methods

2.1. Design

A within-participants design was used with five different sound scenarios with varying intelligibility and meaningfulness of the background speech. As dependent variables, the performance and self-estimated parameters such as disturbance, ability to ignore the background speech, eagerness to go on and quality of collaboration of the participants accomplishing a collaborative task were used. Also, the noise sensitivity and strategy of the participants was measured.

2.2. Participants

A total of 76 participants (37 male and 39 females, mean age = 24.5 years, SD = 4.9 years) took part in the experiment. The participants were Swedish, Belgian and Dutch students. In total 46 Swedish students from the University of Gävle, 24 Dutch students from Avans University of Applied Sciences and 6 Belgian visiting students at the University of Gävle in Sweden participated in this experiment. The Belgian students had the same native Dutch language as the Dutch students. The students worked in couples which resulted in 23 Swedish couples and 15 Dutch speaking couples. One Swedish couple was left out of the analyses because of technical errors. The Swedish and Belgian students received two cinema tickets and the Dutch students received a financial contribution to their study trip to Stockholm and Gävle as a reward for their participation.

2.3. Acoustic conditions

Five sound scenarios were composed, four comprising different background sounds and one quiet condition. In this study intelligibility of background speech was influenced by manipulating the reverberation time by changing the materials of the walls, floor and ceiling of the room. Although absorption of sound is not the only way to influence the intelligibility, it is the most common way to influence the acoustics of an environment. Adding masking sounds or screens to influence the speech intelligibility of an open environment is another possibility to influence the acoustics, however, it takes architectural or electro-acoustical attributes to add to the environment, while choosing materials for walls, floor and ceiling is a standard procedure of an architect designing an open-plan study environment. To study the influence of intelligibility by changing the reverberation time, two extreme sound absorbing conditions were chosen: one condition with only sound absorbing materials on all walls, ceiling and floor and one condition with no sound absorbing materials, resulting in a very short (T = 0.6 s) and very long (T = 2.3 s) reverberation time. To study the influence of meaningfulness of the background speech, the semantic content was manipulated by the language of the background speech. In this experiment Dutch and Swedish language was used due to the possibilities created by the cooperation between the University of Gävle (Sweden) and Avans University of Applied Sciences (The Netherlands).

2.3.1. Acoustic models of two virtual open-plan study environments

To create realistic sound scenarios, the acoustics of an open-plan study environment was modelled with a software package based on geometrical acoustics (Odeon version 12.12 [53]).

For this purpose, the open-plan study environment of the 3rd floor of the Vertigo building at the Eindhoven University of Technology was modelled. This study environment has a height of 5.3 m and a shoe box shape with a volume of 2750 m$^3$ (Fig. 1). A picture of the open-plan study environment can be found in the Appendix (Fig. A2). A comparison between the acoustic parameters calculated using the room acoustics software and acoustic parameters measured in the study environment showed good agreement. The differences between the calculated and measured reverberation times (EDT and T$_{30}$) were smaller than just noticeable differences indicated in literature of 5–8.5% for T$_{5000Hz-10000Hz}$ [54,55]. For the purpose of the auralizations, two new virtual environments were created by changing the materials of the walls, ceiling and floor. One model of the open-plan study environment was calcu-
lated with sound absorbing walls, ceiling and floor resulting in a very absorbing environment (reverberation time $T_{30} = 0.6$ s) and a second model was calculated with reflecting walls, ceiling and floor resulting in a very reverberant environment ($T_{30} = 2.3$ s). In this study the first is called the absorbing model and the latter the reverberant model. The most important materials and absorption coefficients used in the models are presented in Table A1 of the Appendix. Three human talkers were modelled as sound sources and one point as a human receiver. For creating auralizations based on predictions using Odeon, impulse responses were computed for all source-receiver combinations in the two virtual environments.

### 2.3.2. Sound scenarios

In the scenarios, three talkers were implemented producing Dutch or Swedish background speech. As a result, four sound scenarios were created:

- Absorbing open-plan study environment ($T_{30} = 0.6$ s) with 3 Swedish talkers
- Absorbing open-plan study environment ($T_{30} = 0.6$ s) with 3 Dutch talkers
- Reverberant open-plan study environment ($T_{30} = 2.3$ s) with 3 Swedish talkers
- Reverberant open-plan study environment ($T_{30} = 2.3$ s) with 3 Dutch talkers

The position and speech direction of the three talkers and the listening direction of the listener can be seen in the floor plan of the open-plan study environment (Fig. 1). The talkers were positioned at table groups close to the listener. This listener-talker configuration was chosen as an example of a realistic situation for group work in an open-plan study environment.

The background speech consisted of Hagerman sentences (Swedish) [56] and a Dutch version called Matrix sentences [57]. These sentences have been developed for audiological tests measuring speech intelligibility in noise. Each sentence is composed with the same structure of five words (name, verb, number, adjective, object) and each word category can be filled by 10 different words. In this way numerous sentences can be randomly composed. The sentences were recorded in a highly sound absorbing setting and sampled at 44.1 kHz. Ten Dutch and six Swedish students and employees from the Universities of Eindhoven and Gävle have read different Hagerman or Matrix sentences aloud for at least 5 min. From the recordings, three Dutch and three Swedish talkers were selected based on the intelligibility and normal prosody of the spoken sentences. By convolving these recorded speech signals with the calculated impulse responses between the three talker positions and the receiver position (Fig. 1), four sound scenarios were created: Two absorbing Swedish and Dutch sound scenarios and two reverberant Swedish and Dutch sound scenarios. The sound signal in the quiet control scenario was a pink noise signal at the same background noise level as measured in the real study environment without people, 30 dB(A). The sound levels of the separate sources (talkers) at the receiver position as well as the total sound levels for the different scenarios calculated by Odeon are described in Table 1. For the experiment with the collaboration task, the five scenarios were played back through five loudspeakers in a highly absorbing room ($T_{30} = 0.4$ s, Appendix Fig. A1) creating a realistic sound environment. Odeon software was used to create a 2D surround sound based on a specified speaker rig, therefore no HRTF was included in the auralization. Due to the 2D surround sound and the freedom of the subjects to move their heads, there will be some spread to the perception of the loudness of the background speech by the subjects and therefore some uncertainty in the calculated STI values.

The reverberation time of a room will affect the intelligibility of background speech and therefore can influence the disturbance and performance of a semantic task [8,12,39,40]. A comparison of the level of intelligibility of the background speech for the different sound scenarios will be based on a calculation of the speech transmission index (STI) of the background speech. A calculation of the STI was done with talker 3, the nearest and loudest background voice, in accordance with the international standards IEC 60268-

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**Table 1**

Description of the sound sources (talkers) in the absorbing and reverberant model of the open-plan study environment Vertigo floor 3.

<table>
<thead>
<tr>
<th>Talker</th>
<th>Gender</th>
<th>Dutch</th>
<th>Swedish</th>
<th>Absorbing model</th>
<th>Reverberant model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>female</td>
<td>male</td>
<td>46.1</td>
<td>54.7</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>female</td>
<td>male</td>
<td>47.9</td>
<td>54.8</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>male</td>
<td>female</td>
<td>52.2</td>
<td>56.3</td>
<td></td>
</tr>
<tr>
<td>3 talkers</td>
<td></td>
<td></td>
<td>54.3</td>
<td>60.1</td>
<td></td>
</tr>
</tbody>
</table>

---

Fig. 1. Floor plan of the modelled open-plan study environment. Positions of receiver (Listener) and three sound sources (Talker 1–3), with the lines indicating the listening and talking direction. Dimensions in mm.
However, the STI is originally developed to measure speech intelligibility in stationary noise, therefore a calculation of the STI with background speech will be an estimation of the real intelligibility [61]. The background noise level due to the irrelevant background speech was computed as the LAeq and LA95 level of the two other voices. LA95 is the sound level that is exceeded 95% of the time, which is a method to quantify background noise levels of fluctuating signals, i.e. it characterizes the general background sound pressure level that excludes the particular local noise events. LA95 was also used in [62] to estimate the background sound level in an open-plan office to calculate the STI value. Table 2 also shows the calculation of the STI value based on the usual procedure, which does not include the background voices only the stationary 30 dB(A) pink background noise. Due to the low number of talkers and the differences in space angles and distances between listener and talkers (see Fig. 1) it is very difficult to estimate the stationary noise level, therefore a range of estimations is reported in Table 2.

### 2.4. Collaboration task.

The participating students worked in Swedish and Dutch/Belgian couples on a collaboration task. For this purpose, the ‘spot the differences’ task, based on the ‘DiapixUK’ pictures (Fig. 2) developed by Baker and Hazan [63] was used. Two participants had to discover differences between two pictures without seeing each other’s pictures and only using verbal communication. A time limit was set to three minutes, and a maximum of twelve differences could be found in each picture pair. This collaboration task was chosen due to the important vocal communication component (e.g. listening and discussing) in the task in accordance with a collaboration task in an open-plan study environment. Furthermore, this task was suitable for repeated measurements due to the proven equal difficulty of the picture pairs, no learning effect of completing more than one picture and a balanced contribution of both participants [63].

### 2.5. Experimental setup

The participants carried out the test in pairs, seated at a round table in a silent room (60 m², Fig. 3) in a laboratory facility at the University of Gävle. Indoor environmental conditions were kept constant throughout the experiments. The reverberation time of the room was rather short (T₃₀ = 0.4, Appendix Fig. A1). A realistic sound environment was created by a sound set-up consisting of a laptop (Hp Zbook) generating the sound signal via an external sound card (USB Sound Box ST Lab) connected to a sound amplifier (Sherwood RD-7500) lined to five loudspeakers (Cambridge Audio minX). The loudspeakers were set at a height of 1.6 m in a circle surrounding the participants at a distance of 1.4 m (Fig. 3). A screen was placed between the participants (h = 0.3 m above table height) in order to avoid them seeing each other’s pictures. The sound levels of the sound scenarios were calibrated conform the calculated levels by recording the sound signal at both participant positions using a microphone (B&K 4189) and pre-amplifier (B&K type 2671) and subsequently processed off-line with DIRAC 6.0 room acoustics software.

### 2.6. Dependent variables

#### 2.6.1. Performance measurements

As an objective variable of performance, the amount of found differences for each puzzle was used.

#### 2.6.2. Questionnaire scores

As subjective variables the self-rating scores on questions about their experiences during the collaboration task were used. Besides the questions concerning the noise disturbance, other subjective variables were chosen after a pilot study. A difference in eagerness
and motivation during the test was observable, sometimes participants didn’t want to stop after the stop signal. While motivation can influence how subjects react on background speech this question has been added [10]. A difference in collaboration style was also observed during the pilot, therefore a question has been added that maps the self-assessed quality of the collaboration. A seven points Likert scale, 1 until 7, was used for each question.

The questions were:

- the disturbance by the background noise during the task: ‘To what extent did you find the background noise disturbing during the execution of the assignment?’ where 1 represented ‘totally not disturbing’ and 7 ‘very disturbing’
- the ability to ignore the background noise during the task: ‘To what extent could you ignore the background noise?’ where 1 represented ‘it was very difficult to ignore’ and 7 ‘it was very easy to ignore’. There was also a possibility to choose 0: ‘there was no background noise’
- the unwillingness to stop with the puzzle after a time limit set to three minutes: ‘How much did you want to continue with the task despite the time was up?’ where 1 represented ‘not at all’ and 7 ‘very much’
- the quality of the collaboration during the task: ‘How did the collaboration go?’ where 1 represented ‘very bad’ and 7 represented ‘very good’

Also, the self-rated noise sensitivity of the participants was measured by a questionnaire developed by Weinstein [64,65]. The noise sensitivity was measured on the basis of eleven statements in which the participants had to indicate to what extent they agreed with these statements (6-point scale). Furthermore, some couples showed changes in their strategy to find the differences during the pilot. Therefore the participants were asked if they used the same strategy for each picture to find the twelve differences.

2.6.3. Sound measurements

During the execution of the collaboration task, the speech levels of the participants in combination with the background sound scenarios were measured. The sound was recorded at the middle of the round table at a distance of about 0.8 m from the participants (Fig. 3) using a microphone (B&K 4189) and pre-amplifier (B&K type 2671) and subsequently processed off-line with DIRAC 6.0 room acoustics software. These sound measurements are lacking for the first seven Swedish participant couples.

2.7. Procedure

The participants worked on the collaboration task in couples. These couples were participants with the same native language, Swedish or Dutch. The participants had to solve ’spot-the-difference’ puzzles [63] within a time limit of three minutes. Each student was given one picture and was asked to identify the differences through communication with his/her partner. The participants were instructed to use the strategy to start in the left upper corner of the picture and to find the differences by a clockwise description of the pictures. The couples were allowed to change their strategy during the experiment. After a short oral introduction, a training phase of three minutes started to solve the first puzzle to get used to the procedure. The next ten puzzles were presented in the same order to all participants. The sequence of the sound scenarios was different for each couple, they were offered in a counterbalanced sequence using a Latin Square design. The sound scenarios were presented two times after each other for each couple. Each difference on which both participants in a couple agreed on, was marked with a circle at their pictures. Three minutes after starting the puzzle a voice announced to stop searching for differences and to fill in individually a short questionnaire about their experiences during the collaboration task. After finishing the questionnaire an instruction on the computer screen indicated to press a button when they wanted to start the next puzzle. At the same time when pressing the button, a new sound environment started playing in the room. When finishing the last puzzle and the corresponding questionnaire the couples were asked to fill in individually the noise sensitivity questionnaire. The experiment lasted about 50 min for each participating couple.

2.8. Statistical method

The data were analyzed with the statistical program SPSS 23.0. All questionnaire variables were analyzed taking into account individual participants (n = 74). The variables: performance and produced sound level, were measured and analyzed for participant couples (n = 37 for performance, n = 30 for produced sound level).

To study the impact of the background sound scenarios on the collaboration task, for each dependent variable a single-factor repeated measures ANOVA was used to analyze the significance of the differences between the means of the dependent variable due to the five sound scenarios. Furthermore, a follow-up pairwise comparison to examine where the differences occur was performed by using post-hoc T-tests with Bonferroni correction.

To study the impact of language and reverberation time on the collaboration task, for each variable a factorial 2(reverberation: absorbing vs. reverberant) \times 2(language of background speech: native vs. foreign) repeated measures ANOVA was used.

To verify the influence of the noise sensitivity a mean split was done to divide the subjects in two groups and a factorial 2(reverberation: absorbing vs. reverberant) \times 2(language of background speech: native vs. foreign) \times 2(noise sensitivity: low vs. high) repeated measures ANOVA was used to analyze the influence of the noise sensitivity on the dependent variables.

To verify the influence of using the same or different strategies a factorial 2(reverberation: absorbing vs. reverberant) \times 2(language of background speech: native vs. foreign) \times 2(strategy: same vs. different) repeated measures ANOVA was used to analyze the influence of the strategy on the dependent variables.

3. Results

3.1. Impact of background sound scenarios on a collaboration task

The figures in this paragraph show the impact of the different sound scenarios on different dependent variables.

3.1.1. Performance

Fig. 4 shows the performance of participants working on the ‘DiapixUK’ collaboration task while being exposed to different sound scenarios. The different sound scenarios have no significant effect on the performance of the participants (F(4,144) = 0.42, p = .791).

3.1.2. Questionnaire results

Fig. 5 shows the perceived disturbance of participants working on the ‘DiapixUK’ collaboration task while being exposed to different sound scenarios. The different sound scenarios have a significant effect on the perceived disturbance of the participants (F(4,292) = 63.64, p < .001, \eta^2_p = 0.466). The reverberant sound scenarios were reported as being the most disturbing. The quiet condition was reported as being the most comfortable situation. Follow-up T-tests with Bonferroni adjustment showed significant differences between the quiet condition and the four other condi-
tions and between the reverberant native and absorbing (native and foreign) background speech conditions. The differences between all other condition were not significant.

Fig. 6 shows the self-estimated ability of participants to ignore the background noise while working on the 'DiapixUK' collaboration task and being exposed to different sound scenarios. The different sound scenarios have a significant effect on the ability of the participants to ignore the background noise ($F(4,292) = 45.39, p < .001, \eta^2_p = 0.383$). Post-hoc T-tests with Bonferroni adjustment showed significant differences between the quiet condition and the four other background speech conditions. The differences between all the other conditions were not significant.

Fig. 7 shows the eagerness of participants to continue with the 'DiapixUK' collaboration task while being exposed to different sound scenarios. The different sound scenarios have no significant effect on the eagerness of the participants ($F(4,292) = 1.74, p = .141$).

Fig. 8 shows the self-estimated quality of the collaboration of the participants while working on the 'DiapixUK' collaboration task and being exposed to different sound scenarios. The different sound scenarios have a significant effect on the self-estimated quality of the collaboration of the participants ($F(4,292) = 3.11, p = .016, \eta^2_p = 0.041$). The results show that the quiet scenario was reported to have the highest quality. The sound scenarios with background speech in the native language were reported to have the lowest quality. Post-hoc T-tests with Bonferroni adjustment showed significant differences between the means of the quiet condition and the native background speech conditions.
3.1.3. Produced sound pressure levels

Fig. 9 shows the sound pressure levels produced by speech of the participants working on the ‘DiapixUK’ collaboration task while being exposed to different sound scenarios. The different sound scenarios have a significant effect on the produced sound pressure levels of the participants ($F(4,116) = 109.58, p < .001, \eta^2_p = 0.791$). The highest sound pressure levels are produced while being exposed to the reverberant sound environments. The absorbing sound environments and quiet condition result in significantly lower sound pressure levels as can be seen in Fig. 9. Post-hoc T-tests with Bonferroni adjustment showed significant differences between the means of the quiet condition and all other conditions and between the reverberant and absorbing background speech conditions. No significant difference were found between the other sound conditions.

3.2. Impact of the language of the background speech and reverberation of the study environment on a collaboration task

3.2.1. Performance

A factorial 2(reverberation: absorbing vs. reverberant) $\times$ 2(language: native vs. foreign) repeated measures ANOVA with performance as dependent variable revealed no significant main effect of the language of the background speech ($F(1,36) = 0.01, p = .945$) and no significant main effect of reverberation of the study environment ($F(1,36) = 1.57, p = .219$). Also no interaction effect of the reverberance of the study environment and the language of the background speech on performance was found ($F(1,36) = 0.07, p = .788$).

3.2.2. Questionnaire results

Fig. 10 shows the impact of different languages of background speech and the reverberance of the study environment on perceived disturbance of the ‘DiapixUK’ collaboration task. A factorial 2(reverberation: absorbing vs. reverberant) $\times$ 2(language: native vs. foreign) repeated measures ANOVA with perceived disturbance as dependent variable revealed a significant main effect of the language of the background speech ($F(1,73) = 4.45, p = .038, \eta^2_p = 0.058$) and a significant main effect of reverberation of the study environment ($F(1,73) = 11.23, p = .001, \eta^2_p = 0.133$). Fig. 10a shows that native background speech was reported as being more disturbing than foreign background speech and Fig. 10b shows that a reverberant environment perceived more disturbance than an absorbing. No interaction effect of reverberance of the study environment and the language of the background speech on perceived disturbance was found ($F(1,73) = 0.35, p = .559$).

A factorial 2(reverberation: absorbing vs. reverberant) $\times$ 2(language: native vs. foreign) repeated measures ANOVA with the ability to ignore the background speech as dependent variable revealed no significant main effect of language of the background speech ($F(1,73) = 2.20, p = .143$). On the other hand, a significant main effect of the reverberance of the room on the ability to ignore the background noise was shown ($F(1,73) = 5.70, p = .002, \eta^2_p = 0.072$) (Fig. 11). No interaction effect of the reverberance of the study environment and the language of the background speech on the ability to ignore the background noise was found ($F(1,73) = 0.14, p = .788$).

A factorial 2(reverberation: absorbing vs. reverberant) $\times$ 2(language: native vs. foreign) repeated measures ANOVA with eagerness to go on as dependent variable revealed a significant main effect of the language of the background speech ($F(1,73) = 5.98, p = .017, \eta^2_p = 0.076$) (see Fig. 12). On the other hand, no significant main effect of the reverberance of the room on the eagerness to go on with the task was showed ($F(1,73) = 0.03, p = .868$). Also no interaction effect of the reverberance of the study environment...
and the language of the background speech on the eagerness to go on with the task was found ($F(1,73) = 0.64, p = .427$).

A factorial $2$ (reverberation: absorbing vs. reverberant) $\times$ $2$ (language: native vs. foreign) repeated measures ANOVA on the self-estimated quality of the collaboration as dependent variable revealed no significant main effect of the language of the background speech ($F(1,73) = 1.86, p = .177$) and no significant main effect of the reverberance of the room ($F(1,73) = 0.02, p = .885$). No interaction effect of the reverberance of the study environment and the language of the background speech on the self-estimated quality of collaboration was found ($F(1,73) = 0.10, p = .757$).

### 3.2.3. Produced sound pressure levels

A factorial $2$ (reverberation: absorbing vs. reverberant) $\times$ $2$ (language: native vs. foreign) repeated measures ANOVA with produced sound pressure level as dependent variable revealed no significant main effect of the language of the background speech ($F(1,29) = 2.03, p = .164$). On the other hand, a significant main effect of reverberation of the study environment was revealed ($F(1,29) = 93.09, p = .001, \eta^2_p = 0.762$). Fig. 13 shows the impact of the reverberation of the study environment (reverberant, absorbing) for the different background noise scenarios on the produced sound pressure level during the ‘DiapixUK’ communication task. The produced sound level by the participants during the reverberant sound scenarios was higher than the produced sound level during the absorbing sound scenarios. No interaction effect of the reverberance of the study environment and the language of the background speech on the produced speech level was found ($F(1,29) = 0.76, p = .523$).

### 3.3. Impact of the noise sensitivity and strategy of participants on the dependent variables

To verify the influence of the noise sensitivity, a mean split was done to divide the participants in two groups. The mean noise sensitivity of all participants was 3.53 (SD = 0.56) on a 6-point scale. The mean noise sensitivity of the group most sensitive participants (noise sensitivity > 3.53) was 3.91 (SD = 0.34) and the mean noise sensitive of the group participants with the lowest sensitivity (noise sensitivity < 3.53) was 3.03 (SD = 0.37). A factorial $2$ (reverberation: absorbing vs. reverberant) $\times$ $2$ (language of background speech: native vs. foreign) $\times$ $2$ (noise sensitivity: low vs. high) repeated measures ANOVA revealed no significant interactions of the noise sensitivity with one of the dependent variables (performance, perceived disturbance, ability to ignore the background noise, eagerness to go on with the task, self-estimated quality of the collaboration). Because noise sensitivity is an individual characteristic of each participant, the impact of the noise sensitivity on performance and produced sound level, which both are variables of couples, could not be checked.

To verify the influence of changing the strategy of the couples to find the differences in the pictures, a factorial $2$ (reverberation: absorbing vs. reverberant) $\times$ $2$ (language of background speech: native vs. foreign) $\times$ $2$ (strategy: no change vs. changing strategy) repeated measures ANOVA was executed for all dependent variables. The results revealed no significant interactions of the change of strategy with one of the dependent variables.

### 4. Discussion

The aim of this study was to analyze the influence of background speech on performance of a student-collaboration task.
Therefore, participants had to carry out a collaboration task while being exposed to four different background sound scenarios and a quiet sound environment in an open-plan study environment. Speech in the background sound environment was varying in semantic content by changing the language in the background speech, and in intelligibility by changing the reverberation time and, in consequence the sound level in the room (Table 2).

The results show no significant influence of the background sound scenarios on the performance of the participants of the 'DiapixUK' collaboration task. However, the influence of the background sound scenarios on perceived disturbance, the ability to ignore the background speech and the quality of the collaboration of the participants was significant. Also, the produced speech sound levels of the participants were significantly influenced by the background sound scenarios. For all the self-estimated variables the quiet background sound scenario was most appreciated.

4.1. Impact of reverberation time of the open-study environment on the dependent variables

The reverberation time of a room will affect the intelligibility of background speech and therefore could influence the disturbance and performance of a semantic task [8,12,39,40]. Although a longer reverberation time decreases the intelligibility of speech (Table 2), no significant influence of the reverberation time on performance was found. These findings do not fit within a semantic 'interference-by-process' account, as, in line with this account, the performance of a semantic task, such as a collaboration task, should increase due to less intelligible background speech compared to a more intelligible signal [39,40]. After all, less intelligible background speech contains less semantic information compared to a more intelligible signal, therefore, a less intelligible signal should be less disruptive [19]. Furthermore, a less intelligible speech signal will reasonably contain less relevant or interesting information that can capture attention and, as explained by the framework of attentional capture, will disrupt performance less than a more intelligible signal [23].

Table 2 shows a decrease of the STI value due to the longer reverberation time, qualified from 'fair' to 'poor', from 'excellent' to 'fair' or from 'excellent' to 'good'. According to a model of Hongisto, predicting the effect of speech of varying intelligibility on work performance of different tasks [66], performance starts to decrease when STI exceeds 0.2 and the highest performance decrease is reached when the STI is 0.6. Estimated STI values based on $L_{A95}$ are lower than 0.6 (Table 2) and therefore a change in performance can be expected. Estimated STI values based on $L_{A95}$ and the regular STI values vary above 0.6 and despite of a change of intelligibility no change of performance is expected based on Hongisto's model. Some studies have shown that for some complex tasks, like writing [12], word memory and mathematics [67], the largest drop of performance occurs for even lower values of the STI than the original model of Hongisto [66] predicted. In Jahnccke et al. [67] and Keus van de Poll et al. [12], the largest drop of performance occurred between STI values of 0.23 and 0.34. This could be an explanation of the absence of an improvement of performance in this experiment although in any case a significant improvement between the quiet and all other sound scenarios can be expected. Nevertheless, these effects were not found.

An explanation for the increase of disturbance due to a higher reverberation time could be found in the importance of different task components in this complex collaboration task. Although it is impossible to determine the influence of noise on a complex composed task based on the effects of noise on sub-components [68], the analysis of sub-components can give possible explanations of unexpected results found by testing realistic (composed) tasks. Communication by a speech dialog will be very important because negotiating and discussing are important components of a student-collaboration task [17]. The 'DiapixUK' task is an example of a problem-solving collaboration task and contains therefore also an important role for speech communication [63]. Due to less acoustic absorption materials in the reverberant model of the study environment, not only the reverberation time but also the sound pressure level due to noise in a room will increase (Table 2) which will lead to more demanding communication circumstances. As for communication it is well known that with increasing background noise, speakers will raise their speech level to guarantee a sufficient signal to noise ratio for their communication partner [51]. The raised speech levels of the participants can be seen in Fig. 13. So, in this collaboration task, not only semantic cognitive processes but also speech communication is important and both sub-components of the complex collaboration task will respond different to room acoustic parameters such as reverberation time and background sound level.

Semantic cognitive processes prefer background speech with low intelligibility, a result of a long reverberation time in a room, however, speech communication prefers a good signal to noise ratio, a result of a short reverberation time. It seems that the higher sound level of background noise, an additional acoustic result of a longer reverberation time in a room, has a dominant influence on disturbance due to the importance of the vocal communication component in the collaboration task.

4.2. Impact of language of the background speech on the dependent variables

No significant impact of the meaningfulness of background speech on performance was found. On the other hand, the language of the background speech showed to be significantly important for the self-estimated disturbance of participants while performing a collaboration task (Fig. 10a). Participants were significantly more disturbed by background speech in the mother tongue than by background speech in a foreign language. This is in accordance with the 'interference-by-process' account and the framework of attentional capture. The cognitive processes used to automatically analyse the unintended meaningful background speech in the mother tongue will interfere with the similar semantic cognitive processes involved in the execution of a semantic based collaboration task. The background speech in the mother tongue will also capture more attention than the meaningless background speech in the foreign language. These findings correspond with research on reading comprehension [5,6] and proof-reading [7,11] which also show an increasing disturbance by increasing meaningful speech.

The language of the background speech can only have an influence on performance and disturbance if the speech intelligibility is sufficient. Although the estimated STI values (Table 2) give no unambiguous assessment of the level of intelligibility of the background speech, the observed impact of the language of background speech on disturbance indicates intelligible background speech.

4.3. Impact of background sound scenarios on a collaboration task

No significant performance differences were found between the sound scenarios (Fig. 4). Besides the earlier mentioned restricted STI diversity between the sound scenarios and the relatively high STI values (>0.6), these outcomes may also be the result of a limited number of participant couples ($n = 37$), the limited semantic complexity of the collaboration task or the consequence of a ceiling effect the 'DiapixUK' task due the limit of 12 differences that could be found in a puzzle. The latter would imply a non-discriminatory performance measure. However, the statistical results do not provide convincing evidence for this. The median value of the found
differences was rather high (median = 9) but the mean number of participant couples with a maximum score of 12 was only 3 (8%).

Although, no significant differences in performance were found during different sound scenarios, disturbance and ignorance of noise were found to be significantly influenced by the sound scenarios. Self-estimated disturbance differentiates to a greater extent and therefore provides interesting additional data to performance data. An explanation of a more differentiated self-estimated disturbance and less differentiated performance might be an extra effort of participants in solving a task due to feeling disrupted in an adverse sound environment. Schlittmeier et al. [69] call this the ‘reactive effort enhancement’, and this effect can lead to reduced performance differences [69,70].

The eagerness to work on the task was not significantly influenced by the sound scenarios (Fig. 7), for all other self-estimated parameters the quiet scenario was significantly the most preferred sound environment. Unfortunately, a quiet sound scenario is seldom the case in open-plan study environments. Workspaces for one group would be the best environment to work on a collaboration task. Acoustic separated sections within an open-plan study environment would also be a better solution, for instance by using high sound screens. Using acoustic absorbing materials is not enough to create an optimal acoustic environment for a collaboration task in an open-plan study environment.

### 4.4. Impact of the noise sensitivity and strategy of participants on the dependent variables

Although in previous research the influence of noise sensitivity of students on disturbance by noise in open-plan study environments was established [2], no influence of the noise sensitivity score on disturbance or performance was found in this study.

The influence of whether or not using different strategies to find the differences in the ten pictures on the dependent variables was not significant. This confirms the robustness of the ‘DiapixUK’ test. No difference was found between the two groups, which means no learning effect was identified for the group that changed the strategy during the experiment.

### 5. Conclusion and outlook

The hypothesis ‘an increase of intelligibility and meaningfulness of the irrelevant background speech will lead to an increase of disturbance and a decrease of performance of a collaboration task’ is not supported by the results of this study. The sound scenarios with background speech with a combined language and reverberation time intervention showed that an increase of intelligibility and meaningfulness did not lead to an increase of disturbance and a decrease of performance of the collaboration task.

Although sound scenarios with a longer reverberation time result in less intelligible background speech, these background sound environments were the most disturbing. We argue that the sound level, an additional acoustic result of a longer reverberation time in a room, has a dominant influence on disturbance due to the importance of the signal to noise ratio for the vocal communication sub-component in the collaboration task.

The results showed the quiet sound scenario to lead to the lowest level of disturbance, a result in line with the sound level effect, but also in line with the absence of semantic interference. Therefore, it is doubtful if an open-plan study environment is suitable for student collaboration tasks. To create good learning environments applying absorbing materials will not be enough, environments where students can choose to work in quiet zones or a quiet room, as in activity based offices, might be a possible solution.

The ‘DiapixUK’ task is limited in difficulty and performance scale which might have had some influence on the research outcomes. Furthermore, this research also shows that a real and complex sound environment must be taken into account. For instance, an increasing reverberation time in an environment implies also an increasing sound level of the background noise and this combination can have consequences for disturbance and performance of people in work environments. In our setting with three spatially separated background speakers located at nearby table groups we observed a strong effect on vocal communication aspects. It is well possible that this effect was smaller if we had chosen a larger distance between speakers and listener which would have resulted in a lower level of background speech.

Therefore, more research is needed on the influence of the effect of background speech on the performance and disturbance of a collaboration task in open plan study environments. Moreover, this study indicates it is worth to perform more linked research on realistic complex tasks, in real acoustic sound environments to bridge the gap which exists between laboratory findings and applications or practical relevance.

### Acknowledgements

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### Appendix A. Information regarding the acoustic models of the open-plan study environments

#### Table A1

<table>
<thead>
<tr>
<th>Materials</th>
<th>Absorption coefficient</th>
</tr>
</thead>
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<td></td>
<td>125 Hz</td>
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<tr>
<td><strong>Sound absorbing model:</strong></td>
<td></td>
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<tr>
<td>Ceiling: sound absorbing ceiling</td>
<td>0.40</td>
</tr>
<tr>
<td>Floor: carpet</td>
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</tr>
<tr>
<td>Walls: perforated panels</td>
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<tr>
<td><strong>Reverberant model:</strong></td>
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<tr>
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<tr>
<td>Floor: linoleum</td>
<td>0.02</td>
</tr>
<tr>
<td>Walls: unperforated panels</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Figs. A1 and A2

Table A1
Fig. A1. Reverberation Time ($T_{50}$) calculated for the absorbing and reverberant models (by Odeon) and measured in the experimental environment.

Fig. A2. Open-plan study environment, floor 3 Vertigo building, Eindhoven University of Technology.

References


