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The influence of background speech on a writing task in an open-plan study environment

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ABSTRACT

Writing is an important activity in open-plan study environments in higher education. Writing is also a task during which students have indicated to be very disturbed by background speech. The aim of this study was to analyze the influence of realistic sound scenarios in an open-plan study environment on the performance and disturbance of participants working on a writing task, taking into account noise sensitivity as a personal factor. In an experimental setting, participants had to perform a writing task while being exposed to different simulated sound scenarios. These sound scenarios were composed of background speech produced by three or fourteen talkers in a very absorbing (0.6 s) or very reverberant (2.4 s) open-plan study environment. A quiet sound scenario was added as a reference. Results show that the writing performance of participants decreased significantly in the absorbing environment with only three talkers. Although the quiet reference environment was rated as the least disturbing, the performance in the quiet reference condition was not significantly better compared to the other acoustic conditions.

1. Introduction

The impact of the physical environment, including noise and room-acoustics, on the quality of learning at schools has been shown [1,2]. While most studies on school acoustics focus on the impact of room acoustics in classrooms and lecture halls, the acoustics of open-plan study environments certainly require attention as well [3-5]. An open-plan study environment (OPSE) is an informal learning space intended for students to work on their individual and group assignments [4]. As shown in a field study on OPSEs in higher education [4], noise disturbance and lack of sound privacy proved to be the most annoying factors in those environments. Furthermore, this research on OPSEs showed ‘writing’ to be both one of the most frequently performed tasks and one of the tasks where students indicated to be very disturbed by noise [4]. Therefore ‘writing’ is an important task to involve in further research on the acoustics of OPSEs.

To design OPSEs with a high acoustic comfort it will be necessary to get more information about the relation between realistic sound environments, sound disturbance and task performance. In a literature review on human task performance and the indoor sound environment [6], a lack of suitable research, that adds to the knowledge about the influence of a realistic sound environment on people has been brought to our attention. In this research, a conceptual framework is suggested (Fig. 1) that shows the interaction between room acoustics, sound environment and task performance considering other influencing factors. The model implies that the sound environment influences task performance and disturbance. The sound environment is not only determined by the sound sources but also by room acoustic characteristics. Also, important aspects like: personal factors, task type and sound-task interaction can be influencing the relation between sound environment and task performance and disturbance (Fig. 1).

1.1. A realistic sound environment in an OPSE

Most research on the influence of background noise on the performance of cognitive tasks, such as background speech on writing, is performed from a psychological point of view and focuses on understanding cognitive processes by studying how people respond to specific sounds, not how people respond to realistic acoustic environments. The results of most of these laboratory studies are not suitable for translation to realistic settings, specifically OPSEs. For instance, most research on the disturbing effect of background speech on writing tasks is performed...
for sound signals that do not typically occur in OPSEs, such as one background voice combined with white noise [7], rotated speech [8] or pink noise, water waves and multiple voices all with the same sound level [9]. The speech in these studies was recorded in an anechoic environment, and directly offered to both ears of the participants of the experiments by headphones. None of these studies took into account room acoustic parameters such as reverberation time or the implications of spatial aspects such as the position of talkers in relation to the listener in the room. In Keus van de Poll (2018), realistic sounds were used in a study on the effect of multiple voices coming from 2 directions on writing performance [10]. Nevertheless, this study did not take room acoustic parameters such as the reverberation time and sound reflections into account. Room acoustic characteristics will impact background speech; speech in a reverberant room will be louder and less intelligible than in an acoustically absorbing room. Furthermore, the position of talkers in a room will affect the speech levels at the listener position.

In an OPSE, where students work individually as well as in groups in the same room, multiple background voices are coming from various directions and distances. Furthermore, in a realistic OPSE the reverberation time will influence the speech levels and the modulations of the speech envelope [11,12], which will result in different degrees of speech intelligibility and varying values of auditory characteristics of the irrelevant background speech. Therefore, it is useful to model a realistic sound environment, with room acoustic characteristics and multiple background speakers at various places in a room, to study the influence of background noise on a cognitive task such as writing in an OPSE.

1.2. The influence of background speech on a writing task

The type of task determines the influence of the sound environment on performance and disturbance. Writing is a complex task that involves combining new information with information already stored in memory [13]. For example, writing a story requires organizing old and new information into ideas and turn them into a new concept. To create the final story, the concept needs to be reviewed and rewritten [14]. The complex, cognitive processes involved in the writing task are semantic processes, i.e., processes where the meaning of information is of great importance [8].

Research on the influence of background noise on writing tasks showed that especially background speech is very disturbing and influences writing performance [7,8]. In these studies, it is suggested that the disturbance of a writing task by irrelevant background speech is a result of the obligatory (passive) processing of the background speech. This automatic analysis of irrelevant background speech is a semantic process, just like the processes involved in writing. The interference of these simultaneous semantic processes, the processing of the writing task and the unintended processing of the background speech, explains the disturbing effect of background speech on writing [15]. This so-called ‘interference-by-process’ view is a part of the ‘Duplex Mechanism Account of Auditory Distraction’ (DMAAD) [16,17]. This account describes two mechanisms through which sound can disturb cognitive performance. First by ‘interference-by-process’, and secondly by ‘attentional capture’. Disruption of a task due to attentional capture occurs when unexpected changes or aspects in the sound signal capture attention and draw it away from the current task to be executed and thus disrupt performance. Attentional capture mainly depends on the distracting elements in the background noise, and so far, no evidence has been found for the dependence on the type of cognitive task [18].

1.3. Personal factors

Personal factors have been shown to have an effect on the relation between sound environment and task performance and disturbance (Fig. 1) [6,19,20]. An important personal factor is the noise sensitivity of people. In a field study in open-plan study environments [4], disturbance of students by the background noise showed to be related to the noise sensitivity of the students. Other studies on the relation between noise sensitivity and cognitive performance and disturbance found weak or no correlations at all [19,21–23]. To create more clarity on the correlation between noise sensitivity and cognitive performance and disturbance, sound sensitivity is included as a personal factor in this study.

1.4. The aim of the study

The aim of this study is to evaluate the relation between the characteristics of a realistic sound environment of an OPSE, writing task performance and sound disturbance, considering noise sensitivity as a personal factor. This experimental research adds to the existing knowledge on writing performance through creating a more realistic sound environment considering room acoustics (reverberation time) and occupation (number of talkers) of the indoor environment. This study also enhances the knowledge on acoustics of OPSEs, a very important learning environment in higher education. Furthermore, the findings of this research will contribute to filling the gap between more theoretical, psychological research and more realistic sound field research, which is needed to develop design tools that help to make better decisions in the process of building and refurbishing schools.

The hypothesis in this study is that an increase of intelligibility of the background speech, due to varying a realistic sound environment, will lead to a decrease of writing performance and an increase of disturbance. We expect that noise sensitive students will show more disturbance and a larger decrease of writing performance due to the background speech.

![Fig. 1. Conceptual model adapted from Reinten et al. [6] on the effect of room acoustics on task performance and disturbance.](image-url)
2. Materials and methods

2.1. Participants

Forty-Seven Dutch students (29 male and 18 female) aged 16–27 years (mean age 20.4, SD 2.8) participated in this laboratory experiment. These students were recruited by a general call to participate in a writing experiment on the university communication platform. Two students were left out of the analyses (1 male and 1 female) because of technical errors. Two students indicated a light hearing impairment (no use of hearing devices). The data from these students did not differ significantly from the others and therefore were included in the analyses. All students signed an informed consent form before starting the experiment and received a credit voucher for an internet store or free study credits as compensation for participation.

2.2. The sound environment

2.2.1. Modelling sound scenarios

For this writing experiment, realistic background sound scenarios were created by auralizations based on a digital acoustic model of an existing OPSE. In this way five sound scenarios were developed, one quiet (silent) scenario and four sound scenarios with a varying number of talkers in the background and different room acoustic characteristics of the OPSE. The five sound scenarios were offered to the participating students through headphones (Sennheiser 280 Silver) in an experimental setting.

The acoustic model was created by a software package using geometrical acoustics (Odeon version 12.12) [24] and was based on an OPSE intended for engineering students at the Eindhoven University of Technology. The floor plan of the study environment has a rectangular shape and a volume of 2750 m³ (see Figs. 2 and 3). The model in this experiment was used and described in earlier research on the influence of background speech on a collaboration task [21].

To create various sound environments, the materials of the ceiling, floor and walls were modified in the digital model of the OPSE. In this way an acoustically absorbing and an acoustically reverberant model was developed. The virtual absorbing environment consists of acoustically absorbing materials such as sound absorbing ceiling tiles, carpet and perforated wall panels and resulted in a reverberation time of $T_{30} = 0.6$ s. The virtual reverberant environment consists of acoustically hard materials such as a concrete ceiling, linoleum on the floor and unperforated wall panels and resulted in a reverberation time of $T_{30} = 2.3$ s (Table 1).

Furthermore, alternative auralizations were constructed by varying the number of sound sources. One condition was modelled with fourteen human talkers in the OPSE and a second condition was modelled with three human talkers. Every human talker was given its own place in the study environment and its own speech direction. A human receiver was placed in a fixed position and with a fixed listening direction (listener is red in Fig. 3). The fourteen talkers were equally divided over the study environment, and in the least occupied setting three distant talkers were chosen (T4, T8, T12 are blue in Fig. 3). The positions of the listener and the listening direction, and the fourteen talkers and their speech direction, are illustrated in Fig. 3.

The recorded speech used for auralization consisted of students telling stories about their study, hobbies, work, future and holidays. Twenty students were individually recorded in a small sound-absorbing booth and the recordings were sampled at 44.1 kHz. Fourteen different student recordings, from five male and nine female speakers, were selected based on intelligibility, pronunciation and normal prosody of the spoken stories. Accordingly, four stereo sound scenarios were constructed suitable for playback through headphones. This was obtained by convolving, the recorded speech signals with the binaural impulse responses. In both virtual models, three and fourteen talkers were implemented producing background speech resulting in four sound scenarios:

- absorbing OPSE ($T_{30} = 0.6$ s) with 3 talkers
- absorbing OPSE ($T_{30} = 0.6$ s) with 14 talkers
- reverberant OPSE ($T_{30} = 2.3$ s) with 3 talkers
- reverberant OPSE ($T_{30} = 2.3$ s) with 14 talkers

The quiet control scenario consisted of pink noise at a level of 30 dB (A), which was the same level as measured in an unoccupied situation of the real OPSE. The sound levels of the background speech signals from all talkers were modelled at a level of 59.5 dB(A) at a distance of 1 m from the mouth, and the sound power spectrum was in accordance with normal speech [25]. As a result of varying absorption and reflections of the speech signal from talker to receiver, different sound pressure levels occurred for the five sound scenarios. The identical sound power levels at the talker position resulted in the sound power levels presented in
indicates realistic and performance that influences intelligibility
of speech, and the STI value below 0.3 indicates that the speech is almost unintelligible. Noise and reverberation will influence the intelligibility of a speech signal by reducing the modulation depths of a speech signal and thus reduce its intelligibility and STI value. While in numerous experiments the STI is used as a metric to predict performance of a cognitive task [7,9,21], in experiments with realistic sound environments containing background speech, the use of the STI is problematic [21]. This is because the STI is developed for measuring the speech intelligibility of a specific transmission path between one talker and one listener which makes it difficult, if not impossible to determine the STI in a situation with multiple background talkers. To consider talkers in the background environment as noise would not be correct either, as speech is a dynamic sound and STI can only be calculated with continuous noise [26]. Therefore, since irrelevant background speech is the most important background sound source in an OPSE [4], the STI is not very suitable. However, since most literature is related to the STI [7,9,21,27], also this study will include an estimation of the STI values used in the experiment.

Another metric is the Frequency Domain Correlation Coefficient (FDCC), which originated in the field of psychoacoustics to measure the spectro-temporal characteristics of an irrelevant background sound [11, 28]. This relatively new metric is designed to predict the effect that different types of background noise will have on short-term memory performance based on the spectral dynamic character of the noise. Speech is such a sound with a dynamic character and different spectra in

### Table 1
Materials and absorption coefficients for random incidence used in the Odeon models [21].

<table>
<thead>
<tr>
<th>Materials</th>
<th>Absorption coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>125 Hz</td>
</tr>
<tr>
<td>1. Sound absorbing model:</td>
<td></td>
</tr>
<tr>
<td>Sound absorbing ceiling</td>
<td>0.40</td>
</tr>
<tr>
<td>Fabric floor covering</td>
<td>0.05</td>
</tr>
<tr>
<td>Perforated wall panels</td>
<td>0.39</td>
</tr>
<tr>
<td>2. Reverberant model:</td>
<td></td>
</tr>
<tr>
<td>Concrete ceiling</td>
<td>0.02</td>
</tr>
<tr>
<td>Linoleum floor covering</td>
<td>0.02</td>
</tr>
<tr>
<td>Unperforated wall panels</td>
<td>0.08</td>
</tr>
</tbody>
</table>

### Table 2
Description of the sound sources (talkers) in the absorbing and reverberant model of the OPSE in the Vertigo building at floor 3 of Eindhoven University of Technology.

<table>
<thead>
<tr>
<th>Talker</th>
<th>Number of talkers in the model</th>
<th>Gender</th>
<th>Sound level at listener position [dB (A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 talkers</td>
<td>14 talkers</td>
<td>absorbing model</td>
</tr>
<tr>
<td>1</td>
<td>*</td>
<td>male</td>
<td>39.3</td>
</tr>
<tr>
<td>2</td>
<td>*</td>
<td>male</td>
<td>46.5</td>
</tr>
<tr>
<td>3</td>
<td>*</td>
<td>female</td>
<td>44.4</td>
</tr>
<tr>
<td>4</td>
<td>*</td>
<td>male</td>
<td>39.5</td>
</tr>
<tr>
<td>5</td>
<td>*</td>
<td>female</td>
<td>45.9</td>
</tr>
<tr>
<td>6</td>
<td>*</td>
<td>female</td>
<td>44.2</td>
</tr>
<tr>
<td>7</td>
<td>*</td>
<td>female</td>
<td>39.7</td>
</tr>
<tr>
<td>8</td>
<td>*</td>
<td>female</td>
<td>31.8</td>
</tr>
<tr>
<td>9</td>
<td>*</td>
<td>female</td>
<td>28.9</td>
</tr>
<tr>
<td>10</td>
<td>*</td>
<td>female</td>
<td>39.8</td>
</tr>
<tr>
<td>11</td>
<td>*</td>
<td>female</td>
<td>33.5</td>
</tr>
<tr>
<td>12</td>
<td>*</td>
<td>male</td>
<td>35.7</td>
</tr>
<tr>
<td>13</td>
<td>*</td>
<td>male</td>
<td>47.5</td>
</tr>
<tr>
<td>14</td>
<td>*</td>
<td>female</td>
<td>28.8</td>
</tr>
<tr>
<td>pink</td>
<td>noise</td>
<td></td>
<td>30.0</td>
</tr>
<tr>
<td>14</td>
<td>14 talkers</td>
<td>female</td>
<td>53.8</td>
</tr>
<tr>
<td>14</td>
<td>3 talkers</td>
<td></td>
<td>41.1</td>
</tr>
</tbody>
</table>

Fig. 3. Positions of the listener and fourteen talkers (T1-T14), with lines indicating the listening and talking direction.
successive segments. To establish an FDCC value for the background sound, at first the sound must be divided into sequential tokens by localizing high intensities in the sound signal. The window that is subsequently used to select sequential segments is positioned around the local maxima of the envelope and therefore does not have a fixed duration [29]. For normal speech, this token selection process results usually in one token per syllable. For each token, the signal is filtered using 19 one-third octave filters from 125 Hz to 8 kHz. Then the power P is calculated for each band for each token. For a pair of successive tokens, the FDCC is defined by:

$$\text{FDCC} = \frac{\sum_{j} P_{ij} P_{i,j}}{\sum_{j} P_{ij}^2}$$

In this formula, $P_{ij}$ stands for the power spectrum for token $i$ and frequency band $j$. The FDCC value for a speech stimulus is based on the average of these individual correlation values. The FDCC value is approaching 1 if changes in the frequency domain between tokens are minimal, and the tokens are less distinctive and more similar. The lower the FDCC value, the stronger the spectral variation between successive tokens. A decrease of the FDCC value, indicating more variability, is likely to result in a decrease of short-term memory performance [11,29]. Although, this metric has been specifically developed for short-term memory studies, the properties of the FDCC measures (the spectral dynamics of a signal) are strongly related to the intelligibility of speech and therefore also interesting for other cognitive studies.

Both metrics, FDCC and STI, are physical measures, derived from the acoustic properties of the (speech) sounds. Therefore, if we use these metrics to predict the influence of background speech on a writing task, we only estimate the influence of irrelevant background speech based on the physical characteristics of the sound. Both metrics do not take into account semantic aspects such as language, meaning of speech and sentence structure.

2.2.3. STI and FDCC values of the sound scenarios

The intelligibility of the background speech for the listener will be influenced by the reverberation time and by the background noise level in the OPSE [26]. Because speech intelligibility was expected to be of great importance for the writing performance and disturbance, a calculation of the intelligibility of the different background sound scenarios was made. STI values were calculated for the different sound scenarios between the loudest background voice and the listener in each model: talker 13 for the scenarios with fourteen talkers and talker 4 for the sound scenarios with three background talkers (Table 3, Fig. 3). To calculate the STI values, an estimation of the background noise was necessary. Normally, the background noise to determine the STI is a stationary sound, however, in this experiment, and in all OPSEs, the main background noise is irrelevant background speech which is not a stationary sound. To estimate the background noise level due to the irrelevant speech the $L_{Aeq}$ and $L_{95}$ were calculated for the talkers in the different background sound scenarios. The $L_{95}$ is the sound level that is exceeded 95% of the time and is often used to quantify background noise levels of varying and dynamic signals. The approximations of the STI values due to the different reverberation times and estimated background noise levels were calculated by Odeon software in accordance with IEC 60268-16 [26,30]. Furthermore, the STI values without background speech, with 30 dB(A) pink background noise, were calculated for both talkers (13 and 4) as a reference (Table 3).

Also, the frequency domain correlation coefficient (FDCC) for the different sound scenarios was calculated (Table 3) as a measure of spectral variability and as an indicator of the speech intelligibility of the background speech signal [29].

2.3. Writing task

The participating students had to write five stories associated with five different landscapes: mountains, forest, beach, desert and sea. The participants were not allowed to describe the landscapes, they had to create a story connected to the themes. The topics were chosen in accordance with writing experiments of Keus van de Poll [7,9,10].

2.4. Dependent variables

2.4.1. Performance

The performance of writing can be measured by many different quantitative aspects of the produced text but also qualitative aspects like creativity and coherence of the final edited text are possibilities to measure the performance of writing [8]. Earlier research has shown that qualitative aspects of writing were not suitable for measuring the influence of different background sounds on writing performance. A method at which independent judges scores were used to measure the degree of creativity and coherence between the assessors turned out to be low and no difference was measured between the sound conditions [8]. Therefore, in this study the performance of writing is based on the quantitative aspects of the produced text.

The objective indicators to measure writing performance were extracted from the writing process of the participants by using InputLog [31], a key logger that records and observes the writing process. The measured quantitative aspects were the number of typed characters (with and without spaces) and the number of characters (with and without spaces) and words in the final edited text. In order to allow easier comparison with other studies, the values are expressed as values per minute. The number of characters in the final text are all typed characters minus characters that been deleted using delete and backspace keystrokes. Also, the number of pauses longer than one, three and 5 s during the writing session were measured as a performance measure. More characters and words per minute and fewer pauses can be interpreted as a higher performance [7–10].

2.4.2. Self-estimated performance and disturbance

The self-estimated influence of the background sound scenarios on writing performance and disturbance was measured after each writing assignment and different background sound scenario. These measurements were done by presenting four statements to the participants that were to be assessed on a 6-point scale response format. Three statements addressed the influence of the background noise during the writing task (“The background noise during the writing task has influenced:”) the writing speed (“my writing speed and therefore the length of my story”), the quality of the story (“the quality of the content of my story”), the number of writing errors (“the number of writing errors in my story”), and one statement on the disturbance of the participants by the background noise (“The background noise was disturbing”). The 6-point
scale was verbally indicated with "disagree completely - disagree - slightly disagree - slightly agree - agree - agree completely". This questionnaire was offered to the participants in the Dutch language.

After the last writing assignment, the noise sensitivity of the participants was measured. The reduced version of the NoSeQ noise sensitivity questionnaire developed by Griefahn [32] was used. The noise sensitivity was measured via twelve statements in which the participants had to indicate their level of agreement with each statement on a 4-point scale. The 4-point scale was verbally indicated with "disagree completely - slightly disagree - slightly agree - agree completely". This questionnaire was offered to the participants in the Dutch language.

2.5. Design and procedure

A repeated measures, within-participants design was used with five different sound scenarios with varying intelligibility of the background speech by changing the occupancy and reverberation time of the environment. As dependent variables, the writing performance and subjective parameters such as disturbance and self-assessed writing performance of the participants were used. Also, the noise sensitivity of the participants was measured.

The participants were asked to write a qualitatively good story related to a topic. They had to write as quickly as they could and without writing errors. The participants had to use a word processor (msword) to write the story. After a short oral introduction by the experimental researcher a training session started. The participants had to write a story for a period of 2 min to get accustomed to the procedure. The topic was displayed on a computer screen at the start of each writing assignment and for each following assignment the writing period was set to 5 min.

The topics were presented in the same sequence to all participants. The five sound scenarios were offered to the participants by headphones in a counter balanced sequence using a Latin Square design [33]. After each writing assignment the participants filled in a short questionnaire about their experiences during the writing task. After the last assignment the participants had to fill in the noise sensitivity questionnaire according to Griefahn [32].

The experiments were performed at Avans University of Applied Sciences. Participants accomplished the experiment alone in a quiet room (28–32 dB(A)), wearing a headphone, sitting behind a laptop at a desk. The room had one window, facing a street and other buildings. Headphones were used throughout the experiment. The session duration per participant was about 55 min.

2.6. Statistical analysis

For analyzing the data, the statistical program SPSS 23.0 was used. The impact of the background sound scenarios on the writing task was studied by a single-factor repeated measures ANOVA. This was done for each dependent variable in order to analyze the significance of the differences between the means due to the five sound scenarios. Furthermore, to examine where the differences occur a follow-up pairwise comparison was performed by using post-hoc T-tests.

The impact of reverberation time and occupancy on the writing task was analyzed by a two-way repeated measures ANOVA. This was done for each dependent variable by a factorial 2(reverberation: absorbing vs. reverberant) x 2(occupancy: 3 vs 14 talkers) analysis. In this analysis the quiet sound scenario was not taken into account because for the quiet scenario the reverberation time as well as the occupancy was of no relevance.

The impact of the noise sensitivity of the participants on the quantitative and self-estimated qualitative performance of writing was analyzed by a factorial 2(reverberation: absorbing vs. reverberant) x 2 (occupancy: 3 vs 14 talkers) x 2(noise sensitivity: low vs high) repeated measures ANOVA. In this analysis the quiet sound scenario was not taken into account. Also, a factorial 5(sound scenarios) x 2(noise sensitivity: low vs. high) repeated measures ANOVA was performed. For all noise sensitivity analyses the participants were split into two groups, participants with a noise sensitivity higher than the median (median noise sensitivity 2.67) and participants with a noise sensitivity lower than the median.

For all analyses a significance level of 5% was used.

3. Results

3.1. Impact of background sound scenarios on a writing task

The Tables and Figures in this section show the impact of the different sound scenarios on different dependent variables.

3.1.1. Performance

The performance of writing is measured by the number of typed characters and words and the number of pauses, while participants were writing the stories and being exposed to the five sound scenarios. In Table 4 the mean number of characters is shown for the five different background sound scenarios. The ANOVA only shows a significant effect of the five background sound scenarios for the number of characters in the final text without spaces. Further, pairwise comparisons show that only the performance in the '3 talkers-absorbing' sound scenario is significantly lower than the performance in all other background sound scenarios (included the quiet sound scenario) (p < .034).

The performance of writing is also measured by the number of words per minute in the final text. In Table 4, the mean number of words is shown for the five different background sound scenarios. The ANOVA

<table>
<thead>
<tr>
<th>Quantitative performance measures</th>
<th>Background sound scenarios</th>
<th>F (4,176)</th>
<th>( \eta^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characters</td>
<td>quiet condition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typed characters per minute incl. spaces</td>
<td>234.75</td>
<td>229.32</td>
<td>231.96</td>
</tr>
<tr>
<td>Typed characters per minute excl. spaces</td>
<td>195.36</td>
<td>190.14</td>
<td>189.00</td>
</tr>
<tr>
<td>Characters per minute in the final text incl. spaces</td>
<td>186.41</td>
<td>184.48</td>
<td>184.14</td>
</tr>
<tr>
<td>Characters per minute in the final text excl. spaces</td>
<td>152.25</td>
<td>150.21</td>
<td>150.54</td>
</tr>
<tr>
<td>Words</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Words per minute in the final text</td>
<td>34.35</td>
<td>34.25</td>
<td>33.66</td>
</tr>
<tr>
<td>Pauses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of pauses &gt; 1 s</td>
<td>29.60</td>
<td>31.04</td>
<td>29.64</td>
</tr>
<tr>
<td>Number of pauses &gt; 3 s</td>
<td>6.11</td>
<td>6.56</td>
<td>5.84</td>
</tr>
<tr>
<td>Number of pauses &gt; 5 s</td>
<td>2.44</td>
<td>2.60</td>
<td>2.29</td>
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</table>

*\( p < .05 \).
shows a significant effect of the five background sound scenarios for the number of words in the final text. Further, pairwise comparisons show that only the performance in the ‘3 talkers-absorbing’ sound scenario is significantly lower than the performance in all other background sound scenarios (p < .033) except for the performance in the ‘3 talkers-reverberant’ sound scenario (p = .079).

The number of pauses is also a performance measure, fewer pauses indicate a higher performance. The number of pauses is measured for pauses longer than one, three and 5 s. In Table 4, the mean number of pauses is shown for all three time conditions for the five different background sound scenarios. The ANOVA only shows a significant effect of the five background sound scenarios for the number of pauses longer than 3 s. Further pairwise comparisons show that only the number of pauses in the ‘3 talkers-absorbing’ sound scenario is significantly higher, implicating a lower performance, compared to all other background sound scenarios (p < .030) except for the ‘14 talkers-reverberant’ sound scenario (p = .095).

The size effect of the significant performance differences between the ‘3 talkers-absorbing’ sound scenario and the other sound scenarios ranged from 8.2 to 10.6 characters per minute, or 41 to 53 characters for the story written in 5 min. This results in a maximum decrease of performance of 7.1% in the intelligible ‘3 talkers-absorbing’ sound scenario in comparison to the other sound scenarios. The performance decrease in words was 11–15 words for the story written in 5 min, with a maximum decrease of 8.8%. Finally, the maximum increase of the number of pauses longer than 3 s was 7.7%.

### 3.1.2. Self-estimated performance and disturbance

The self-estimated influence of the sound scenarios on the quality of the writing task was measured by a questionnaire after each writing assignment. In Table 5 the mean scores (on a 6-point scale) are shown for the five different background sound scenarios. The ANOVA shows a significant effect of the five background sound scenarios on all the quality items: the quality of the story, the writing speed and the number of errors. All self-estimated variables show significant differences between the means. The participants estimated the number of writing errors to be the least influenced by the background speech and the writing speed to be the most influenced by the background sound scenarios. Pairwise comparisons show that the influence of the ‘quiet’ background sound scenario on the quality variables is significantly lower in comparison to all other background sound scenarios (p < .001). Also, the ‘14 talkers-absorbing’ sound scenario has a significantly lower influence on the self-estimated correctness of spelling in comparison to the ‘14 talkers-reverberant’ sound scenario (p = .050).

The perceived disturbance due to the sound scenarios during the writing task was also measured by the questionnaire after each writing assignment. In Table 5 the mean values of the disturbance scores on a 6-point scale for the five different background sound scenarios are presented. The ANOVA shows a significant effect of the five background sound scenarios on disturbance. Further pairwise comparisons show that the perceived disturbance during the ‘quiet’ background sound scenario is significantly lower in comparison to all other background sound scenarios (p < .001). Also, the disturbance due to the ‘14 talkers-absorbing’ sound scenario is significantly lower in comparison to the ‘3 talkers-absorbing’ sound scenario (p = .034).

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Means for self-estimated influence of background noise on different quality aspects of a writing task.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qualitative performance measures</td>
<td>Background scenarios</td>
</tr>
<tr>
<td></td>
<td>quiet condition</td>
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<tr>
<td>Self-estimated quality measure</td>
<td></td>
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<tr>
<td>Quality of the story</td>
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<tr>
<td>Writing speed</td>
<td>2.60</td>
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<tr>
<td>Number of writing errors</td>
<td>2.40</td>
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<tr>
<td>Self-estimated disturbance</td>
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<tr>
<td>Perceived disturbance</td>
<td>2.10</td>
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</table>

*p < .01.

<table>
<thead>
<tr>
<th>Table 6</th>
<th>Results (means) of a factorial 2 by 2 analyses on reverberation and occupancy by a repeated measures ANOVA for different dependent variables.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantitative performance measures</td>
<td>Effect of:</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Characters per minute in the final text excl. spaces</td>
<td>Reverberation</td>
</tr>
<tr>
<td></td>
<td>Occupancy</td>
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<tr>
<td></td>
<td>Revurb*Occup</td>
</tr>
<tr>
<td>Words per minute in the final text</td>
<td>Reverberation</td>
</tr>
<tr>
<td></td>
<td>Occupancy</td>
</tr>
<tr>
<td></td>
<td>Revurb*Occup</td>
</tr>
<tr>
<td>Number of pauses &gt; 3 s</td>
<td>Reverberation</td>
</tr>
<tr>
<td></td>
<td>Occupancy</td>
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<tr>
<td></td>
<td>Revurb*Occup</td>
</tr>
<tr>
<td>Self-estimated performance measures</td>
<td>Effect of:</td>
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<td></td>
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<tr>
<td>Self-estimated quality of story</td>
<td>Reverberation</td>
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<tr>
<td></td>
<td>Occupancy</td>
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<td></td>
<td>Revurb*Occup</td>
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<tr>
<td>Self-estimated writing speed</td>
<td>Reverberation</td>
</tr>
<tr>
<td></td>
<td>Occupancy</td>
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<tr>
<td></td>
<td>Revurb*Occup</td>
</tr>
<tr>
<td>Self-estimated number of writing errors</td>
<td>Reverberation</td>
</tr>
<tr>
<td></td>
<td>Occupancy</td>
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<td></td>
<td>Revurb*Occup</td>
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<tr>
<td>Perceived disturbance</td>
<td>Reverberation</td>
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<td></td>
<td>Occupancy</td>
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<tr>
<td></td>
<td>Revurb*Occup</td>
</tr>
</tbody>
</table>

*p < .05, **p < .01.  

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3.2. Impact of reverberation time and occupancy of the study environment on a writing task

The impact of both the reverberation time and occupancy of the study environment was tested by a two-way ANOVA for all dependent variables. As can be seen in Table 6, the reverberation time of the study environment has no significant main effect on the measured quantitative or self-estimated qualitative performance parameters. Also, the occupancy has no significant main effect on the self-estimated qualitative performance parameters. However, there is a significant main effect of occupancy on the produced number of words in the final text. An interaction effect for reverberation and occupancy has been shown for the number of pauses longer than 3 s and for perceived disturbance.

3.3. Impact of the noise sensitivity of participants on a writing task

Analyses showed that only the quantitative performance measures were significantly influenced by the noise sensitivity of the participants. A significant interaction effect between reverberation, occupancy and noise sensitivity was found for the number of characters in the final text without spaces (F(1,43) = 4.67, $\eta^2_p = 0.10$, p < .036), for the number of words in the final text (F(1,43) = 5.03, $\eta^2_p = 0.11$, p < .029), and for the number of pauses longer than 3 s (F(1,43) = 5.46, $\eta^2_p = 0.11$, p < .024). No significant interaction effect of the noise sensitivity of the participants was found for the self-estimated parameters. Fig. 4 shows the influence of the sound scenarios on the performance of writing for the participants with the lowest and highest noise sensitivity.

The results show that the participants with the lowest noise sensitivity performed significantly lower (p < .006) in the ‘3 talkers-absorbing’ sound scenario, the most intelligible speech sound scenario, in comparison to the other sound scenarios. The results of the participants with the highest noise sensitivity showed no significant differences between the means of the performances in different sound scenarios. On the other hand, this group of participants showed a significantly lower performance score than the lower noise sensitivity participants of the experiment (Fig. 4).

4. Discussion

4.1. Impact of the sound scenarios on a writing task

4.1.1. Performance

The impact of a realistic sound scenario on writing performance, measured by the number of characters (without spaces), words and pauses above 3 s, is significant. It is shown that the ‘3 talkers-absorbing’ sound scenario, the sound scenario with the highest speech intelligibility and lowest FDCC value, has a significantly lower writing performance score for all three performance indicators. The calculated STI value of 0.62/0.52 (Table 3) for the ‘3 talkers-absorbing’ sound scenario, is the highest STI value and led to the lowest writing performance score. In this sound scenario the writing performance decreased 6–7% for characters and 8–9% for words compared to the sound scenario with the lowest STI value (STI = 0.18/0.12), i.e. the ‘14 talkers-reverberant’ sound scenario and the ‘quiet’ sound scenario. The STI-performance model of Hongisto [27] and writing experiment results of Keus van de Poll [7] also showed a decrease of approximately 7% in writing performance due to more intelligible background speech with a higher STI value. A performance decrease was expected in this experiment; however, it was not clear what percentage to expect in more realistic sound scenarios. A further validation of the performance model of Hongisto for all STI values is difficult to establish due to the limited number of STI values in this research (only four) and due to the difficulty of translating realistic dynamic sound scenarios into STI values.

The lowest performance score during the sound scenario with the lowest occupancy (3 talkers) and lowest reverberation time (0.6 s) of the study environment can be explained by the ‘interference-by-process’ view [15]. This sound scenario has the highest speech intelligibility (highest STI and lowest FDCC value) of the background speech on the listener’s position, and therefore will lead to an increase in the interference of two semantic processes: the unintended interpretation of the background speech and the writing process [15]. Consequently, this will result in a performance reduction of writing.

![Fig. 4](image-url)  
Fig. 4. Mean values and confidence intervals (95%) of quantitative performance writing parameters (number of characters and words in the final text and number of pauses > 3s) during different background sound scenarios for the group of participants with the lowest and highest noise sensitivity.
4.1.2. Self-estimated performance and disturbance

The impact of a realistic sound scenario on the self-estimated writing performance of the participants is significant. Results show that the participants estimated the ‘quiet’ sound scenario to significantly have the least influence on their writing performance. On the other hand, the participants did not identify the sound scenario with significantly lowest writing performance, the most intelligible ‘3 talkers-absorbing’ sound scenario, as the most disturbing sound scenario.

The impact of the sound scenarios on perceived disturbance was significant. However, we must consider that pairwise comparisons showed no significant differences between the disturbance means of the different sound scenarios except for the means in comparison to the ‘quiet’ condition.

Therefore, we can conclude that there is a difference between the influence of a realistic sound scenario on the quantitative writing performance in comparison with the influence of the same realistic sound scenarios on the self-estimated writing performance. Background speech with the highest estimated STI value and lowest FDCC value (3 talkers-absorbing) decreased the writing performance the most, while this intelligible background sound scenario was not rated as the most disturbing background sound scenario. Also, whereas the ‘quiet’ sound scenario was rated as least disturbing, this scenario is not the sound scenario with the significantly highest performance.

Moreover, we can conclude that background speech is disturbing, the students rated the background speech as slightly disturbing or disturbing while they rated the quiet condition (30 dB(A) background noise) as not disturbing (Table 5).

4.2. Impact of the reverberation time and occupancy of the study environment on a writing task

No significant main effect was found for the reverberation time of the study environment. A significant main effect of occupancy was only found for the number of words as a performance indicator. Also, an interaction effect for reverberation time and occupancy was found for the number of pauses >3 s and for perceived disturbance (Table 6).

The level of speech intelligibility in the sound scenarios is determined by the reverberation time in combination with the number of background talkers (Table 3). Therefore, based on the presumed importance of the speech intelligibility [7,8,15], a main effect of the reverberation time and occupancy on the output measures was expected. However, the effects shown in this analysis are not consistent, a few dependent variables show significant effects in line with the expectation, but most variables show no effect of the reverberation time or occupancy.

4.3. Impact of the noise sensitivity on a writing task

A significant influence of the noise sensitivity of the participants was found on the quantitative writing performance indicators. Results show that people with high noise sensitivity have significantly lower performance scores (Fig. 4). Also, a significant interaction effect between reverberation, occupancy and noise sensitivity was found for writing performance.

As shown in Fig. 4, the worst-case scenario with regards to performance of the participants with the lowest noise sensitivity scores is the ‘3 talkers-absorbing’ sound scenario, the scenario with the highest STI and the lowest FDCC value. The participants with the highest noise sensitivity scores do not have a preferred or adverse sound scenario were performance significantly improves or deteriorates. In general, the noise sensitive participants perform significantly lower than less noise sensitive participants. This applies to all sound scenarios, with exception of the ‘3 talkers-absorbing’ sound scenario, this intelligible sound scenario also reduces the performance of the participants with the lowest scores for noise sensitivity. It shows that noise sensitive people are disturbed by all sound environments and people less sensitive to noise are mainly disturbed by intelligible speech.

4.4. STI and FDCC as a predictor of performance and disturbance of a writing task

Although the intelligibility of the background speech is a good predictor of the performance and disturbance of a writing task, the speech transmission index (STI) is not such a suitable predictor in a realistic sound environment. The background noise in an OPSE is mostly irrelevant speech from students consulting each other and working on a group assignment. A usual way to calculate the STI value does not include background speech, only stationary background noise signals. Therefore, it is difficult to calculate and use the STI value in such a realistic sound environment as a predictor of intelligibility, in a realistic sound field STI is merely an estimation. The FDCC value, on the other hand, is not developed to measure the intelligibility of speech, this psychoacoustic metric is developed to predict how sound influences specific cognitive processes. It measures the spectral variation and segmentation of background noise. Intelligible speech will show spectral variation and will result in a lower FDCC value. The results of this experiment show that the sound environment leading to the lowest performance and the most disturbance, is the sound scenario with the lowest FDCC value, and the least disturbing quiet sound scenario shows the highest FDCC value. The advantage of the FDCC value in comparison with the STI value is the possibility to measure (calculate) the FDCC value of all sound scenarios, also the ‘quiet’ and the dynamic background speech scenarios, while the STI can only estimate the dynamic sound scenarios and not the ‘quiet’ sound scenario. Furthermore, the FDCC metric measures the dynamic characteristic of the sound scenarios in a multi-talker scenario at the listener’s position, while the STI can only measure one talker-listener position at the same time.

Despite all the advantages of the FDCC value, it is not a metric developed to measure the speech intelligibility. A negative correlation can be found between the estimated STI values compared to the calculated FDCC values (Table 3), with the highest correlation for the STI values based on the L495 background noise. However, based on this experiment it is not clear whether the FDCC value or one of the estimated STI values are the best predictors of writing performance.

4.5. Towards acoustic recommendations for OPSEs

Current recommendations on open-plan work environments focus on realizing a reduction of the sound level of irrelevant speech over distance to reduce the speech intelligibility of the irrelevant background speech [35-37]. In order to be able to realize such a rapid decrease of sound level over distance, acoustic consultancies will advise the application of sound absorbing materials and the use of acoustic screens [35, 37]. Although such measures will reduce the sound level of the irrelevant speech, the speech intelligibility will still be high compared to the same irrelevant speech in a more reverberant environment. It is important to find the right balance between absorption and reverberation in an environment. An increase in absorption results in a decrease of the sound level from irrelevant background speech and will increase the intelligibility of the background speech [36]. In contrast, reverberation will reduce the modulation depths of a speech signal and thus reduce its intelligibility [26,29,30], but will increase the overall background sound level. The optimal balance will be influenced by the kind of tasks being performed in the environment and their sensitivity to intelligible speech and high background noise levels [21].

Especially in an OPSE, reducing the intelligibility of background speech through room acoustic design is very important [4]. After all, the combination of different tasks in an OPSE, group assignments producing speech and individual (semantic) tasks, is an important cause of the disturbance of students by intelligible background speech.

This research shows that the least disturbance and the least decrease of self-estimated performance occur in a quiet environment. Therefore,
we plead for activity based OPSEs, with plenty of individual silent workplaces that are acoustically separated from group work places.

5. Conclusions

The results of this study, that distinguishes itself by using realistic sound scenarios, show that the intelligibility of background speech significantly influences the performance and disturbance of students working on a writing task in an OPSE. The lowest performance on a writing task was measured in an absorbing environment with a low occupancy rate, a situation with intelligible background speech. This is in line with earlier studies, mainly conducted from a psychological perspective [7,8,15], and also in line with our hypothesis.

Given the practical point of view of this study, our results are an important contribution to the evidence that an increase in intelligibility of background speech will lead to a decrease in performance. We see the relevance of this result in the fact that current recommendations on open work environments often lead to very sound absorbing environments [35–37], which in itself will lead to an acoustically optimal performance with increase speech intelligibility if no additional measures are taken.

The second part of our hypothesis was not confirmed by the data in this study. We expected noise sensitive students to be more disturbed and to show a larger decrease of writing performance due to the intelligible background speech compared to the less noise sensitive students; this effect was not established. However, this study did show noise sensitive people to be disturbed by all sound environments, while less sensitive people were mainly disturbed by intelligible speech. Nonetheless, all people consider a very quiet OPSE without irrelevant background speech to be the least disturbing.

The findings of this research are the beginning of gathering data that will contribute to the development of design tools that help to make better decisions in the process of developing an acoustically comfortable open-plan study environments. In the future, more realistic student tasks must be tested in environments with different acoustic parameters, for instance by changing the reverbation time in a room, changing the decrease of sound level over distance using screens or changing the background sound level and spectrum.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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