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The indoor sound environment and human task performance: A literature review on the role of room acoustics

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A B S T R A C T

A substantial amount of studies have addressed the influence of sound on human performance. In many of these, however, the large acoustic differences between experimental conditions prevent a direct translation of the results to realistic effects of room acoustic interventions. This review identifies those studies which can be, in principle, translated to (changes in) room acoustic parameters and adds to the knowledge about the influence of the indoor sound environment on people. The review procedure is based on the effect room acoustics can have on the relevant quantifiers of the sound environment in a room or space. 272 papers containing empirical findings on the influence of sound or noise on some measure of human performance were found. Of these, only 12 papers complied with this review's criteria. A conceptual framework is suggested based on the analysis of results, positioning the role of room acoustics in the influence of sound on task performance. Furthermore, valuable insights are presented that can be used in future studies on this topic. While the influence of the sound environment on performance is clearly an issue in many situations, evidence regarding the effectiveness of strategies to control the sound environment by room acoustic design is lacking and should be a focus area in future studies.

Contents

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1. Introduction

People working indoors are continuously subjected to sound. Whether working alone in a private office, or amongst a large number of colleagues in an industrial setting; a complete absence of sound never occurs. Conversations of colleagues, loud industrial noise or the continuous hum of HVAC installations can be distracting [1], cause stress [2], fatigue [3] or even hearing loss [4], all of which might result in a decrement of task performance. Sound though, can also be stimulating or cause a positive mood change which might in turn result in a performance increase [5]. Already in the early 20th century, studies on the relation between sound and people's performance were conducted [6], and the increasing popularity of open-plan offices in recent years has boosted this field of research [7].

The substantial amount of research dedicated to the effect of sound on human performance, mainly originates from a cognitive psychology point of view. For example, many studies are performed in which people's susceptibility to distraction by noise is used to understand the processes in the human brain [8]. The results of these studies are then introduced as evidence to support psychological theories about selective attention [9], interfering processes [10,11] and arousal [12]. Building on the increasing knowledge about the impact of sound on performance, the current review takes a complementary perspective. Rather than focusing on understanding cognitive processes, we are taking a room acoustic point of view following the working principles of evidence-based building design [13]. Furthermore, the scope of this study is limited to the effect of natural sound sources occurring in working environments on task performance. We consider this an important step in defining the prerequisites of a good indoor environment, a topic for which the awareness of its importance has grown in recent years [14,15]. A good sound environment should not lead to any physical, physiological or psychological changes in a person's body that could negatively affect his or her health. Furthermore, the sound environment should allow a person to be in, or should even contribute to obtaining, the most suitable state of mind for a specific activity. What we consider to be lacking in the literature is an overview of the effect of sound on human performance which can be, in principle, translated to room acoustic parameters and adds to the knowledge about the influence of the built environment on people. While letting a person perform a serial recall task when being subjected to either speech at 85 dB(A) or 'silence' in a laboratory experiment (for an example see [16]) does provide insight in cognitive processes, it does not help define guidelines for an optimal acoustic (working) environment. These extreme levels are not representative of natural working conditions; moreover, room acoustic interventions or design decisions alone would not allow to realize such large differences between conditions. The question arises to what extent the current body of evidence on the effect of sound on task performance can be used to gain insight in the role of room acoustics.

The present paper reviews to what extent the current evidence on the effect of sound in the work environment on human performance can be used to aid room acoustic design decisions. To answer this question, it is desirable to clearly specify what effect (passive) room acoustics can have on the relevant quantifiers of the sound environment in a room or space. Based on this, the results can be identified of those experimental studies in which the difference between experimental conditions can, in principle, be attributed to room acoustic modifications. A secondary objective of this review is to derive implications for future research from the results. The meta-analytic synthesis conducted by Szalma and Hancock [17] in which the results of 151 papers on the effect of sound on human performance were reviewed will form the starting point in the search for literature.

2. Search strategy and selection of papers

2.1. The effect of room acoustics on the indoor sound environment

For this review's purpose, sound level and speech intelligibility are considered the most important quantifiers of the sound environment that are affected by room acoustics and for which the effect on human performance has been investigated and published. Inclusion and exclusion criteria for the selection of papers which do not take room acoustics into account are based on a theoretical approach of the maximum effect of room acoustics on these quantifiers. Other effects of acoustics on the sound environment, such as the existence of a flutter echo which can make one's own voice sound unnatural and uncomfortable, or a change in the spectral distribution of sounds due to frequency specific sound absorption, are too dependent on the source type and the positions of source and receiver, and will therefore be considered to be outside the scope of this review. Studies on the effect of actual room acoustic changes are included.

The inclusion and exclusion criteria that are used to select articles are shown in Table 1. The following sections provide a motivation for the inclusion criteria related to sound levels and speech intelligibility and an explanation of the review procedure.

2.2. Motivation for the inclusion criteria related to sound levels and speech intelligibility

2.2.1. Reduction of overall sound level in a room of a fixed size due to sound absorption

Replacing a sound reflecting ceiling with a ceiling with a high sound absorption coefficient, adding wall panels or absorbing elements in the room and the use of soft furnishings are typical ways to increase the total amount of sound absorption. The sound pressure level difference $\Delta L_p(f)$ due to adding sound absorbing material to a room, assuming a diffuse sound field, can be calculated by using the following formula (1). The total amount of room absorption area in m^2 before (S_1) and after (S_2) the intervention has

Table 1
Inclusion and Exclusion criteria for three review rounds.

Review round	Inclusion	Exclusion
1 Based on titles only.		- All papers of which the topic was unrelated to sound or acoustics.
2 Based on abstracts only.	- Study contains empirical evidence on the influence of sound or noise on some measure of human performance. - Subjects are between 18 and 65 years of age (working population). - Subjects are healthy, without reported hearing loss.	- Indirect effects of sound (health outcomes, performance outcomes as a result of hearing loss). - Review papers (no methods included). - Papers not published in English.
3 Based on full papers.	The difference between the control situation and the experimental situation must be attributable to a passive room acoustic change. This means that the descriptions below apply: - The sound source in both control and experimental situation must be of equal origin and behavior. - The maximum difference in sound level between control and experimental situations is 25 dB for studies comparing different sound levels of 1 sound source. - The maximum difference in general sound level between control and experimental situations is 11 dB for multitalker speech and broadband noise. - The maximum difference in general sound level between control and experimental situations is 6 dB for sound sources other than speech and broadband noise.	- Studies in which a difference in speech intelligibility is created in a manner that cannot be realized by passive room acoustic interventions. - Studies during which the subjects are exposed to sound levels higher than 85 dB(A). - Studies in which one sound condition is compared to a completely silent condition. - Studies in which an ambient noise condition is compared to a different experimental sound condition. - Studies in which an active sound masking system is used.

to be known. The formula is only valid outside the direct sound field of a source.

$$\Delta L_p(f) = 10\log_{10}\left(\frac{S_2(f)}{S_1(f)}\right) \tag{1}$$

For the purpose of this review the assumption was made that a feasible difference in the amount of absorption area (S) between a fairly reverberant space and a very sound absorbing space is a quadrupling of S at most. From formula (1) it can be easily deducted that this will lead to an overall sound level reduction of 6 dB. The fact that it is easier to absorb high frequencies than low frequencies is not taken into account here. Therefore, the reduction of sound level in a room due to added absorption is considered to be a maximum of 6 dB. When the sound source is speech, there are however reports of cases in which the sound level reduction after a room acoustic intervention exceeds this physical reduction [18]. The explanation can be found in the Lombard effect, which describes the observation that speakers raise their speaking level when the background level increases [19]. Increased vocal output as a function of room absorption in multitalker situations was investigated in an experimental setup [20]. Results indicate that, in a multitalker situation, per doubling of the amount of absorption area, the sound level is reduced by 5.5 dB. In the case of quadrupling the amount of absorption the sound level reduction would then reach 11 dB. A maximum difference of 11 dB between control and experimental conditions, in the case of multitalker speech or informationless background noise, is introduced as one of the inclusion criteria for this review. For other source types the maximum difference between control and experimental conditions is 6 dB, since the Lombard effect does not apply here.

2.2.2. Reduction of sound level from a single sound source

Increasing the absorption of a ceiling and placing sound blocking, screening and absorbing elements between a single source and a receiver will increase the spatial decay of sound [21,22]. This means the effect of sound absorption increases with the distance from the source. The difference in sound level resulting from a single sound source at 4 m from that source can be as large as 13 dB for two extreme situations (reflecting walls and ceilings, without screens, versus absorbing walls and ceilings and high sound screening and absorbing panels) [22]. At 16 m from the source however, this difference can be as high as 25 dB [23]. These results are based on a single sound source at a certain distance such as a human voice, a telephone or a machine and do not take into account any other sources in the same room. A maximum difference of 25 dB is introduced as inclusion criterion for studies comparing the effect of a single voice or single sound source. In the case of speech however, the absolute levels at which the speech is presented should be realistic as well. At 1 m distance from the speaker, the sound level caused by human speech is approximately 60 dB(A) [24], and the absolute levels of speech should be related to the level difference that is introduced.

2.2.3. Speech intelligibility

The intelligibility of speech is influenced by room acoustics. Reducing reverberation by adding sound absorption will improve speech intelligibility at short source-receiver distances (within the direct sound field) while reducing speech intelligibility at longer distances as a result of a steeper decay of sound level. A common parameter to describe speech intelligibility between a source and a receiver is the speech transmission index (STI), a dimensionless number between zero and one [25]. A perfect speech intelligibility results in an STI value of 1, whereas a value below 0.3 leads to almost unintelligible speech. Another effect of increasing the amount of absorption in a room is the reduction of background noise which increases the speech intelligibility if the listener is close to the sound source, i.e. when the direct sound dominates the sound heard by the listener over the reverberant sound. This complexity makes it hard, if not impossible, to introduce a range of STI difference as an inclusion criterion as the source and receiver positions could be different in each situation. In selecting studies for inclusion, papers in which conditions with varying levels of speech intelligibility are compared have to be carefully analyzed.

To provide insight in the inclusion and exclusion of studies that compare different levels of speech intelligibility, three studies are discussed here. Liebl presents the results of a study on the combined effects of acoustic and visual distraction [26]. Although all other inclusion criteria are met, the study is excluded based on the method used to achieve the different acoustic situations. In order to create a difference in the speech intelligibility of the signal presented to the subjects, a filter was applied to a speech signal of high intelligibility, based on the insulation properties of a plasterboard wall. The original signal and the filtered signal were then presented at the same sound level during both good and bad speech intelligibility conditions, accompanied by a masking sound originating from the computer's fan control. The reason for exclusion was the fact that the sound in both good and bad speech intelligibility conditions was presented at the same sound level. If, due to screens and absorbing panels the speech intelligibility of a distant source were reduced, this would in reality lead to a reduction of the sound level at the receiver position as well, and therefore an even lower speech intelligibility. While this study provides insight in the effect of degraded speech, the conditions cannot be translated to room acoustic differences.

Another approach was found in a study by Schlittmeier et al. [27]. The effect of background speech varying in intelligibility on three different tasks is investigated in a laboratory setting. A German speech signal was presented at 55 dB(A) in one of the conditions. Two auralized versions of this signal were presented at 35 dB(A), both based on a specific insulation curve of either a double wall with low-pass characteristics or a light wall, representing a mobile wall or screen. Only the comparison between the signal at 55 dB(A) and the 35 dB(A) auralization of a light wall is of interest for this review. The level difference between these two situations is feasible if the distance between source and receiver is more than 10 m and the study is therefore included. When interpreting the results of this study, however, it has to be taken into account that both signals were presented through headphones in a sound attenuated booth and no other background noise was present. In a realistic situation, the lowered speech signal would have been masked by background noise which is always present and would therefore have been less intelligible.

A third example of a study on the effect of speech intelligibility on task performance is described in Venetjoki et al. [28]. Here, a speech signal mixed with background noise is presented to the subjects. The level of the speech signal in the 'intelligible' condition is 48 dB(A), presented at a signal to noise ratio of 13 dB. To create a less intelligible condition, the level of speech is reduced by 8 dB(A) which is feasible when absorption and screens are added to a room. The background level for this condition was however increased by 13 dB(A), representing an active masking system. The study was excluded based on the increased background level.

2.3. Search strategy

The search strategy to find relevant studies is based on the reference list of Szalma and Hancock's review [17] and two additional literature searches. The search terms that were used in Szalma and Hancock's meta-analysis, (noise OR speech) AND (memory OR decision-making OR problem-solving OR attention OR vigilance OR tracking OR marksmanship OR shooting OR fine motor OR gross motor), were found to be incomplete for the aim of this study as no terms related to room acoustics were used. Furthermore, the cut-off date for their review was February 2011. Therefore the search strategy by Szalma and Hancock was repeated for the period of 2011–2016 (cut-off date January 2016), and an additional search was conducted using more search terms related to acoustics and less specific performance indicators. Another difference is the addition of terms relating to the work environment such as 'employee' and 'ergonomics', which was deemed necessary to reduce the search results to a feasible amount. The search terms included in the additional literature search, based on the PICO strategy [29], are depicted in Fig. 1. The search was conducted in Pubmed, ScienceDirect and PsychINFO (using Ovid) to cover a broad area of research. No search terms were used for the comparison (C) part of the PICO strategy, since the decision to include papers is not based on methodological aspects.

After gathering the results of the two searches, three review rounds were performed to select studies that met the inclusion criteria according to Table 1. In the first round article titles were screened, after a removal for duplicates, to exclude all titles that had no relation with the topic. Since the search terms included the word 'sound' which also means 'good' the initial search results contained a substantial amount of unrelated articles. In the second review round abstracts were screened based on the inclusion and exclusion criteria which are shown in Table 1. As abstracts do not contain all relevant methodological information, no studies were excluded based on room acoustic theories in this round. The second review round's criteria are similar to the inclusion and exclusion criteria as used by Szalma and Hancock [17], so that after this round the papers from their review could be added to conduct the third review round. Full text versions of all available papers in the third round were collected to start searching for studies in which the difference between control and experimental situation can theoretically be a result of room acoustic modifications and studies in which the results of a room acoustic intervention are presented. Since the decision whether to include papers in this round is based on the specific experimental conditions of each study, review papers are excluded. For each paper, the following study characteristics were obtained: task/performance measure, type of sound used, and the experimental conditions. The decision to include or exclude the study was based on this information. The review procedure and the number of papers selected in each step is shown in Fig. 2.

2.4. Method of analysis

During the selection process, information on the subjects' age, the sound sources which were used, the conditions that were

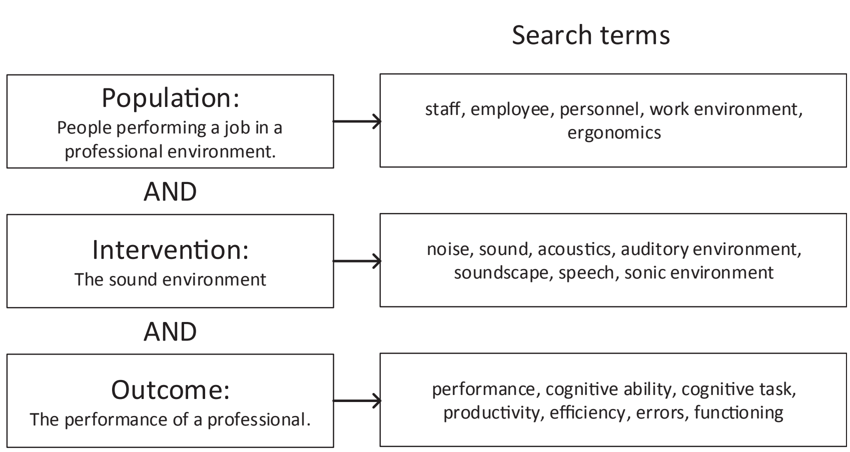

Fig. 1. Search terms used in the additional literature search.

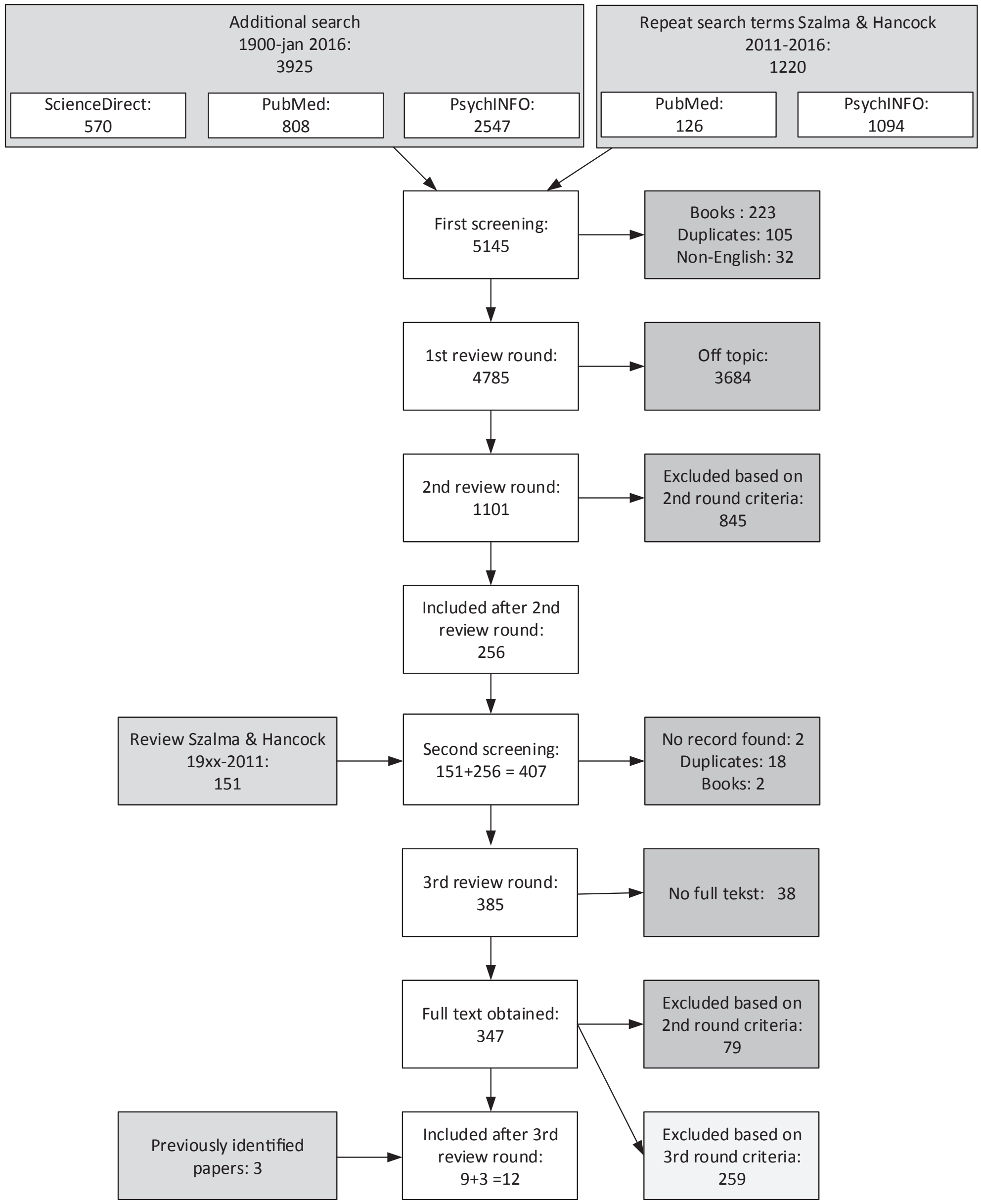

Fig. 2. Review procedure and overview of selected and excluded numbers of papers.

created and the type of task was already collected. Further categorization of the 12 remaining papers after the third review round is based on the outcomes of each study, and the factors that may have influenced or determined these outcomes. Therefore, information on the subjects' other personal factors, the type of room that the study was conducted in or refers to was collected and a translation to room acoustic parameters, if applicable, was made. In the comparison of study outcomes, these methodological aspects of the studies were taken into account.

3. Results

The very broad scope of the literature search and corresponding search terms led to a substantial amount of studies in which some variable of the auditory environment was altered in order to measure the effect on human performance. After removing duplicates, books and papers not written in English, 4785 papers were included in the first screening round which was performed by the first author. Based on titles only, 3684 papers were excluded. Papers on the performance of speech-language pathologists, noise induced hearing loss and the development of 'sound' methodologies, designs or practices are well represented within the excluded papers. The abstracts of the remaining 1101 papers were thoroughly read to identify studies fitting the second round inclusion criteria. In the case of any doubt, the paper was included, leaving 256 papers to be studied in the third round together with 129 (without duplicates and books) papers from Zsalma and Hancock'review. Full text versions of 38 papers could not be obtained, these were excluded so that an analysis of the remaining 347 papers could be performed.

Methodological information from all the papers was gathered by the first author based on which the decision was made whether the paper could be used to determine the effect of room acoustics on human performance. During this process, 79 papers were retrospectively excluded based on 2nd round exclusion criteria. Then, based on third round inclusion criteria, the collection was narrowed down to a total of 9 papers which were identified by the described search strategy and 3 more papers which were added as they were previously identified by the first and second author. Checking the reference lists of the final set of included papers did not lead to any more inclusions, however, more papers were found that would comply with the criteria of the 2nd screening round. These studies have not been processed in the results.

3.1. Results overview

An overview of the methodological aspects and outcomes of the 12 included papers (covering 24 studies in total) is presented in Table 2. Source characteristics, room typology, performance measure and personal factors (if reported) are given as well as the study outcomes. Some of the included studies report on multiple sound conditions which do not all comply with the inclusion criteria of this review. The statistical analysis of those studies does not always provide the required information for this review's purpose, those outcomes are marked with an asterisk.

A first observation when looking at Fig. 2 is the relatively small number of papers that could be included in the third review round as compared to the amount of papers in the second review round. From Table 2 it can be read that there are five papers in which actual room acoustic conditions are modified to measure an effect on performance, either by physically changing a room [33,40] or by using auralizations [30,38,44]. The remaining 7 papers were identified from which the theoretical effect of room acoustics on human performance could be deducted. The last column of Table 2 provides a short analysis of each study.

4. Discussion of results

In the previous section, the experimental conditions and outcomes of each study were translated to the effect of a possible room acoustic intervention on task performance. To analyze the data in Table 2, a distinction is made based on the role and type of sound in each experiment, which can be either a distractor [20,27,32,33,38,40,45], or part of the task [36,37,39,43,44]. Three types of sound were used in the studies considering sound as a distractor:

- speech [27,32,33];
- broadband noise [45];
- and typical office sounds [30,38,40] (e.g. typing, printing, speech, walking sounds).

Speech and a masking sound are used in studies [36,37,39,43,44]. Here, speech is part of the task, and a higher speech intelligibility is assumed to improve task performance. The outcomes suggest that for situations in which communication through speech such as lectures, presentations and meetings is a regular activity, performance of hearing, processing and remembering the speech content is affected by the signal-to-noise ratio of the presented speech. In these situations a slightly higher signal-to-noise ratio, which can theoretically be achieved for short speaker-to-listener distances through adding sound absorbing material to a room, has a positive effect on serial recall performance [37,43], free recall [36], auditory processing and memory [39] and comprehension of a classroom learning task [44]. The experimental conditions of the studies cannot easily be compared. Both positive and negative SNR's were used and the differences between conditions within each study vary as well as the masking sounds that were used. Overall though, the results of these studies are consistent, a higher speech intelligibility improves performance, dependent on the working memory capacity of the subjects [36,39], and task difficulty [37,43].

In studies [27,32,33] speech is considered a distractor, and the level of intelligibility, determined by actual room acoustic properties [33], the sound level at which the speech is presented [32], or both [27] are used as the independent variable. Again, comparing the outcomes is hard, as the actual speech signals which were used in the experiments (speech in a foreign language, multitalker speech and semantically meaningful sentences) are very different. Lowering the level of speech in a foreign language from 40 dB to 20 dB, which could theoretically be realized by increasing the amount of sound absorption in a ceiling and adding sound absorbing and blocking partitions, improves serial recall performance, while a smaller difference does not show this effect [32]. In the multitalker situation, however, a physically built sound absorbing ceiling and absorbing screens seem to reduce serial recall performance (statistical significance not determined due to other experimental conditions). The use of different sound sources could be one of the reasons for these contradicting results. Based on the included studies, the effect of room acoustics on human performance is unclear when speech is seen as a distractor [27,32,33]. Given the many studies on the irrelevant speech effect [46–48] this is an unexpected finding. Furthermore, the results imply that the effect of room acoustics on human performance is dependent on the task and on personal factors [33].

One study is included which reports the effects of the level of white noise on serial recall performance [45], in this case the difference between conditions can only be attributed to acoustics (combined with the Lombard effect) if the white noise is seen as multitalker speech. No significant effect of noise level was found, but interaction effects indicate that the effect of noise is task dependent.

The third sound type, office noise, is used in three of the included studies [30, 38, 40. Only one of the three studies using office noise reports an effect on performance [30], but as other conditions were included in the experiment, we could not determine the statistical significance. Again the outcomes are task dependent, proofreading performance (finding errors in a text) was worse in the reverberant condition compared to the other two conditions, while the speed of text typing was slower in the absorbent condition. A reason for not finding significant differences in [38] could be the relatively small difference (reverberation time of 0.7s vs 0.9 s) between conditions. In [40], no effect of the room acoustic modifications was found for a subjective measure of performance, while subjects did report lower perceived disturbances and stress. People might underestimate the effect of the sound environment on their own performance, as seen in [49] where subjects performed significantly worse on an objective proofreading task in noise in contrast to their own belief.

Based on these eligible papers for this study, it seems that the effect of room acoustics on human performance is dependent on the sound source and its relation to the job or task, on the task itself and on the personal factors of the person performing the task. We argue that knowledge on job characteristics, the sound sources including their relation to the (expected) task at a workplace and, if possible, personal factors of employees is a prerequisite to create a good room acoustic design. This can be visualized in a conceptual model on the effect of room acoustics on human performance.

4.1. Conceptual model

Our conceptual model, depicted in Fig. 3, is based on the obvious but important separation between room acoustics and the sound environment. It is the sound environment that influences task performance, not room acoustics. Room acoustics, though, does influence the sound environment. The model is furthermore based on general room acoustic principles, and the results of the papers

Table 2
Summary of the papers included after the third review round. The table provides all available information about the subjects' personal factors (age, working memory capacity (WMC), occupation), the number of subjects (N), the type of sound source used in the study, the conditions that subjects were subjected to, the type of room that the study was performed in or should represent, the type of performance which is measured and whether it is a complex task or an ability (explained in the discussion section) and reported outcomes. The last column provides the current authors' interpretation of the conditions and results. An indicates that no statistical analysis is available, as not all study conditions can theoretically be achieved by room acoustic changes.

Ref.	Personal factors	N	Source type	Conditions	Room type	What is measured	Outcome	Interpretation
[30]	Mean age = 22.	15	Recorded office noise, containing speech.	Recorded office noise trough a 7 + 1 speaker system in 3 conditions: 1. Recording adapted in auralization software (ODEON), model includes a sound absorbing suspended ceiling. Average SPL = 52 dB(A) 2. Condition 1 + added sound absorbing baffles and screens. Average SPL = 49 dB(A). 3. Condition 1 + absorbing ceiling replaced with reflective ceiling. Average SPL = 54 dB(A). No information on actual reverberation times or absorption coefficients.	Participants are seated in a mock-up office, 5 desks in center of room. The auralized recordings represent an open office. More details can be found in [31].	A: Proofreading (complex). B: Text typing (complex). C: Addition task (ability). D: Self estimated performance (subjective).	A: Performance decrease in reverberant condition compared to 'real' and absorbent conditions. (falsely detected errors only) B: Speed of text typing shows a clear decrement in the sound-absorbent office compared to both the reverberant and the 'real' office. C: No effects of sound absorption on addition performance were found. D: No visible effects of sound absorption found on self-estimated performance.	Actual acoustic modifications are used to create the different conditions, a theoretical translation to room acoustics is therefore not needed There is a lack of information with regard to the room acoustic conditions. Reverberation times, decay of sound or speech intelligibility are unclear. Furthermore, the original recordings are not made in an anechoic chamber. The outcomes are task dependent, and suggest that too much sound absorbing materials in an office environment could increase distraction by irrelevant speech for some tasks. Statistical significance cannot be determined, however.
[32]	Students. Age unclear.	72	Irrelevant speech in foreign language, single speaker.	Speech monaurally presented at: 1. 70 dB. 2. 76 dB. Sound delivered through headphones.	Sound attenuated room.	Serial recall of visually presented letters. (ability)	The results indicate a slightly larger percentage of errors in the 76 dB condition (Noise minus quiet performance: ~16% vs ~13%), the effect is not statistically significant.	The level difference of a single voice is 6 dB between the two conditions in this experiment, this could theoretically be the case in two similar spaces in which the amount of absorption material in the 'louder' condition is a quarter of the amount in the more quiet condition. The levels used in this experiment (>70 dB) represent a situation in which the speaker is close to the listener in an otherwise 'quiet' room. The listener is, however, in the reverberant field. The results suggest that in a quiet environment, with irrelevant speech (foreign) at a close distance, doubling the amount of absorption material does not lead to a higher visual short term memory performance level.
	Students, age unclear.	80		Speech binaurally or dichotically presented at: 1. 20 dB. 2. 40 dB. 3. 50 dB. Sound delivered through headphones.	Sound attenuated room.	Serial recall of visually presented letters. (ability)	The results indicate a larger percentage of errors in the 40 dB condition compared to the 50 dB condition for the dichotically presented sound (Noise minus quiet performance:~18% vs ~7%). An opposite and smaller effect (Noise minus quiet performance: ~9% vs. ~12%) was found for the binaurally presented sound. Both differences do not represent a statistical significant effect. The results show a performance difference between the 20 dB and 40 dB conditions which was found to be statistically significant.	The 10 dB level difference between conditions 2 and 3 can theoretically be attributed to room acoustics in the case of a single speaker at a distance of several meters from the speaker in a reverberant room compared to a more sound absorbing room which includes sound absorbing screens between the source and the receiver. In such a case, the level difference of irrelevant (foreign) speech does not lead to a higher short term memory performance. The level of speech is 50 dB or lower, which implies that the speaker is at a distance of several meters from the listener. Adding higher or more screens with sound blocking and absorbing properties between the speaker and the listener could lead to condition 1, and cause a significant visual short term memory performance increase.

(*continued on next page*)

Table 2 (*continued*)

Ref.	Personal factors	N	Source type	Conditions	Room type	What is measured	Outcome	Interpretation
[33]	Age 19-45, m = 23.9. Noise sensitivity measured by NoiSeQ [34]	97	Multitalker speech at varying distances from the receiver (2–6 m).	Speech at 53 dB played through 4 speakers at different positions in the room. Two conditions: 1: Sound absorbing ceiling (EN 11654 [35], class A, total area 75 m^2) and walls (class A, 18 m^2), 1.7 m high sound absorbing screens (EN 11654 [35], class B, one-sided area) STInear = 0.8 STIfar = 0.42 2: Sound reflecting ceiling and walls, 1.3 m high sound reflecting screens. Total absorption area is 142 m^2 less than in condition 1. STInear = 0.7 STIfar = 0.6.	Open-plan laboratory office in which acoustic conditions were physically realized. 8.9 × 9.4 × 2.55 m.	A: Serial recall of visually presented digits. (ability) B: n-back task (ability) C: Operation span (ability) D: Text memory task (complex).	A: Worse performance in condition 1 during serial recall task, largest difference in noise sensitive group. Statistical significance unclear B: Condition 1 shows shorter reaction times during n-back task. Statistically insignificant. No effect of noise sensitivity. C: No statistical significant effect of noise condition or noise sensitivity. D: No statistical significant effects of the conditions on text memory performance. No interaction effect for working memory capacity and acoustic condition.	Actual acoustic modifications are used to create the different conditions, a theoretical translation to room acoustics is therefore not needed The results suggest that in an open office environment with multiple speech sources at various distances the effects of room acoustic changes on the performance of an n-back task, operation span and text memory is nonexistent. The effect on visual short term memory, task A, is undetermined. In their paper, the authors discuss several factors that could explain the statistical insignificance of the measured effects. These include both methodological limitations and the practical limitations of room acoustic design.
[36]	Age 19-35. Working memory capacity, high and low.	35	Speech in white background noise.	Speech signal in 4 different conditions, sound level unknown. 1: (SNR +12 dB, STI 0.73) 2: (SNR +9 dB, STI 0.64) 3:(SNR +6 dB, STI 0.55) 4: (SNR +3 dB, STI 0,46) Sound delivered through headphones.	Sound isolated test room.	Free recall of aurally presented words (ability).	A significant effect of SNR on memory performance was found for subjects with low WMC. Largest decrement between conditions (SNR +12 dB, STI 0.73) and (SNR +9 dB, STI 0.64). No effect of SNR on memory performance found for subjects with high WMC. No effect of WMC on speech intelligibility for the different SNR conditions.	The difference in speech intelligibility is created by adding background noise. This can theoretically correspond to a situation in which a listener is within the direct sound field of a speaker while the overall level of background noise varies as a result of more sound absorbing material. The results can be translated to lecture or presentation settings.
[37]	Age 20-24.	26	Speech in multitalker babble.	Signal in multitalker babble, 2 conditions. 1: SNR -5 dB 2: SNR -10 dB Sound delivered through headphones.	Single-walled sound attenuated chamber.	Serial recall of words, aurally presented (ability).	Performance in the first three serial positions is best in the low noise (SNR -5 dB) condition, whereas noise level had no influence on performance in the last two serial positions.	The difference in speech intelligibility is created by adding background noise. This can theoretically correspond to a situation in which a listener is within the direct sound field of a speaker while the overall level of background noise varies as a result of more sound absorbing material. The more difficult task is in this case more (negatively) influenced by noise. The results can be translated to lecture or presentation settings.
[38]	Age 18-25.	42	Mixed anechoic recordings of various office sources, presented at 65 −75 dB(A).	The recordings are played in simulated rooms with different reverberation times: 1: 0.7 s 2: 0.9 s. Sound delivered through headphones.	Testing took place in a standard laboratory. Conditions represented 'typical offices'.	Serial recall of visually presented items (ability).	No differences in recall performance between the two auditory conditions at any serial position.	Actual acoustic modifications (modeled) are used to create the different conditions, a theoretical translation to room acoustics is therefore not needed. The reverberation times of 0.7 s and 0.9 s can be representative of an office, more details such as spatial decay and source receiver conditions are needed to be able to generalize the results to actual working conditions. The results suggest that lowering the reverberation time in a typical office from 0.9 s to 0.7 s does not affect visual short term memory.

[39]	Age 22 −45, m = 31.6. Working memory capacity.	39	Speech in stationary speech shaped noise (SSN).	Signal in SSN, 3 conditions. 1: SNR -2 dB. 2: SNR -4 dB. 3: SNR -6 dB. Sound delivered through headphones.	'Quiet office'.	Auditory and memory processing. The task requires hearing, remembering and processing of semantic content (complex). The task comprises 3 memory load levels.	Memory performance decreased with worse SNR for subjects with high working memory capacity only. No main effect of SNR was found.	The difference in SNR is created by adding background noise. This can theoretically correspond to a situation in which a listener is within the direct sound field of a speaker while the overall level of background noise lowers as a result of more sound absorbing material. The results can be translated to lecture or presentation setting, lower background noise can lead to better auditory and memory processing of listeners with a high WMC.
[40]	Office employees.	40	Field study, actual office noise.	Three physically built acoustic conditions. 1: Baseline: absorbing ceiling ($\alpha_w = 0.95$). 2: Worse acoustics: 55% of tiles replaced by reflective ceiling tiles ($\alpha_w =$ ~ 0.05). 3: Better acoustics: absorbing ceiling & wall panels ($\alpha_w = 0.95$).	Open-plan office with an atrium in the middle.	Self- rated professional efficacy Subscale of the Maslach Burnout Inventory [41] (subjective).	No significant effect of room acoustic changes on self-rated efficacy was found.	Actual acoustic modifications are used to create the different conditions, a theoretical translation to room acoustics is therefore not applicable. The two conditions represent realistic circumstances. Parameters of interest are the decay of sound and speech intelligibility for various source receiver conditions. A detailed measurement report can be found in [42] No objective outcome measurements were conducted. The results imply that there is no difference in perceived efficacy of office workers between a sound absorbing and a rather reverberant office. The perception of disturbances and cognitive stress, however, were reduced in the sound absorbing condition.
[27]	Age 19-27. Age 19-38. Age 20-37.	20 24 28	Speech: semantically meaningful sentences.	1. Speech signal of high intelligibility at 55 dB(A). 2. The same speech signal auralized based on the insulation properties of a lightweight screen or partition, 35 dB(A). Sound delivered through headphones.	Double walled sound proof booth.	Serial recall of visually presented items. (ability). Mental arithmics (ability). Verbal- Logical reasoning (complex).	1: 41% error rate. 2: 39% error rate. No significant difference. 1: 36% error rate. 2: 34% error rate. No significant difference. 1: 27% error rate. 2: 27% error rate. No significant difference.	The difference between the two conditions of interest can theoretically be achieved in a large office with a single speaker at a distance of at least 10 m. Sound absorbing and insulating screens should be placed between source and receiver to create condition 2. The results imply that such an intervention does not cause a significant effect in visual short term memory, attention (concentration) and the more complex task of verbal-logical reasoning. The lack of background noise in both conditions could be a reason for not finding differences. In all three tests, condition 2 was rated as less disturbing than condition 1.
[43]	Students. Age unclear.	60	Speech and white noise.	Speech signal at 65 dB in white noise in two conditions: 1. SNR +10 dB. 2. SNR +5 dB. Noise conditions were either mixed and presented randomly or blocked and predictable. Presentation mode undefined.	Undefined.	Serial recall of aurally presented syllables (ability).	Results are presented as a function of serial position, separate results are presented for subjects who received random noise conditions and for subjects receiving predictable noise conditions. Significant reduction of short term memory performance for condition 2 in the random presentation mode, largest effect is seen in the most difficult serial positions. In the case of predictable presentation mode, a reduced performance in seen only for the final two serial positions in condition 2.	The difference in SNR is created by adding background noise. This can theoretically correspond to a situation in which a listener is within the direct sound field of a speaker while the overall level of background noise varies as a result of more sound absorbing material. In the case of a 5 dB difference, this would mean that the amount of absorption material in condition 1 would be almost double the amount in condition 2. The results can be translated to lecture or presentation setting, lower background noise can lead to a better auditory short term memory performance.
[44]	Age 19-32, m = 25.8.	40	Speech in band-pass filtered noise.	Speech signal at 60 dB in noise in 4 conditions: 1. (SNR +10 dB, RT 0.6 s). 2. (SNR +10 dB, RT 1.5s). 3. (SNR +7 dB, RT 0.6 s). 4. (SNR +7 dB, RT 1.5 s). Sound delivered through multiple speakers in the room.	Simulated classroom of 18 m^2. Corresponding with presented sound conditions.	Comprehension of a classroom learning task in two different presentation modes, discussion and lecture (complex).	Interaction effects were found for condition (lecture or discussion) and SNR, and for condition and RT. Comprehension scores were more affected by SNR and RT in the discussion condition than the lecture condition. Adverse acoustics (SNR +7 dB, RT 1.5 s) led to lower comprehension scores. The results indicate a stronger effect of SNR than of RT.	Actual acoustic modifications (modeled) are used to create the different conditions, a theoretical translation to room acoustics is therefore not applicable. The task and the simulated environment have a high ecological validity and can be translated to classroom settings.

(*continued on next page*)

Table 2 (*continued*)

Ref.	Personal factors	N	Source type	Conditions	Room type	What is measured	Outcome	Interpretation
[45]	Students. Age unclear.	80	White noise.	White noise in two conditions: 1: 65 dB(C). 2: 75 dB(C). Sound delivered through headphones	Undefined.	A: Free recall of visually presented associated words. Including semantic orienting (ability). B: Free recall of visually presented non-associated words. Including semantic orienting (ability). C:Free recall of visually presented associated words (ability). D: Free recall of visually presented non-associated words (ability).	No significant main effect of noise was encountered. In the orienting tasks (A&B), subjects performed better in 75 dB(C), condition 2, for both associated and non-associated lists. Subjects performed better under condition 1 in the non-orienting tasks (C&D). The experiment also included a 85 dB(C) exposure condition. For the non-associated lists, this condition improved performance compared to the lower noise exposures in the non-orienting task and reduced performance in the orienting task.	White noise is used, with a difference between conditions of 10 dB. This can only be an effect of room acoustics in a multitalker situation (babble). Quadrupling the amount of absorption area in a space with multiple speakers in the reverberant field could theoretically cause the difference between condition 1 and 2. The results can be translated to a large office setting with multiple speakers, e.g. a call center. The effect of lower background noise is dependent on the task content even if the same ability (visual short term memory) is measured.

eligible for this review The results of studies which were included in the second review round but excluded in the third review round are used to explain and strengthen the model.

The indoor sound environment is, considering a well-insulated area, determined by both the sound sources and the room acoustic properties of the space. There is no sound environment, and therefore no effect of room acoustics without a sound source. Multiple studies on the effect of sound on human performance show that this effect is dependent on the type of source and its behavior. In reviews by Suter [50] and Szalma and Hancock [17] it is concluded that intermittent sound has a more disruptive effect on performance than continuous sound, and unfamiliar or unexpected sounds show an even larger performance decrement. Another example can be found in Marsh, Hughes and Jones [10] who show that meaningful speech has a more disruptive effect than meaningless (e.g. foreign language) speech on a semantic task.

Room acoustic parameters are the result of a room's shape, volume and materialization. The sound environment is characterized by the combination of room acoustic parameters which means, for example, that the resulting sound environment in rooms with equally long reverberation times and the same sound source could still be very different. Furthermore, room acoustic parameters are dependent on the location of both the sound source(s) and the receiver in a room. For each combination of space typology (narrow corridor vs open plan space), source type, behavior and location, the effect of sound absorbing materials on the auditory environment can be determined. The effect of room acoustics on the sound environment can only be generalized towards those situations which are similar in these aspects.

The results of this review suggest that task type influences the effect of the sound environment on task performance [30,33,37,43–45], which is in line with [17]. A closer look at the term 'task performance' reveals that performance in itself is task dependent, the type of task (and its complexity) therefore also has a direct influence on task performance. Personal factors were also revealed as aspects that influence the effect of sound on human performance. Other than noise sensitivity [34] and working memory capacity [36,39], there are several more personal factors of which the moderating role on the effect of sound on people's performance has been established. Examples can be found for emotional state such as sadness [51] and introversion [52]. Furthermore, as people age, their hearing ability deteriorates, especially for higher frequencies [53]. This affects, amongst others, speech intelligibility, the ability to discriminate speech against a background and the ability to detect the direction from which sounds are originating [53]. Similar to task type, personal factors can both influence task performance directly, and influence the effect of the sound environment on task performance.

An obvious difference in the outcomes of included studies was observed based on the role of the sound environment for a task, the sound-task interaction is therefore included in the model. Finally, as research has shown that the integration of information from different sensory systems is a fundamental characteristic of perception and cognition [54], other environmental factors are included in order to offer an integrated approach for room acoustic design.

4.2. Implications based on the model

The conceptual model in Fig. 3 illustrates the complexity in defining the role of room acoustics in the effect of sound on human performance. Each aspect included in the model has been shown to influence the outcomes. They are, therefore, important factors to take into account in the interpretation of studies or the design of an experiment aimed to gain knowledge on the role of room acoustics

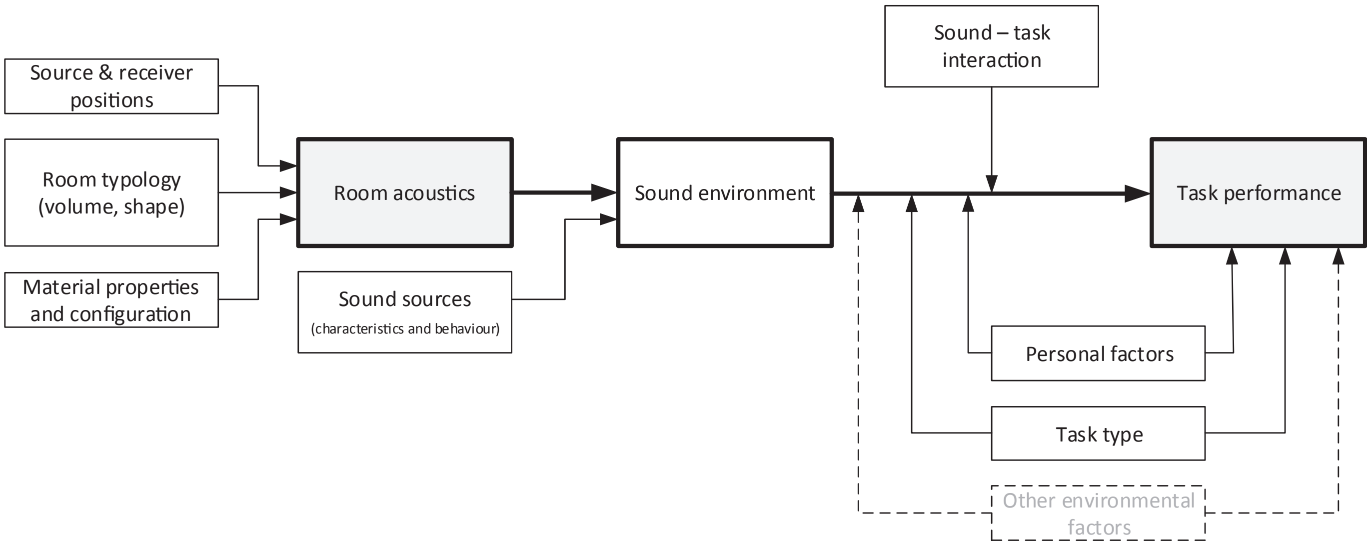

Fig. 3. Conceptual model on the effect of room acoustics on task performance.

on human performance in a natural work setting. In the sections below, recommendations for future research are presented based on each aspect of the model.

4.2.1. *Sound sources*

The sound sources in a workplace are in most cases largely determined by the type of job that is performed there and the user habits (it is obvious that the main source of sound in a call-centre, human speech, is very different from that in a small chemical laboratory with a few people doing very concentrated and individual work). Yet only the combination of sound sources that is typical for an office environment was used as an experimental sound in the included studies. It was seen that it belongs to the most used sources (along with speech and broadband) in the excluded studies as well. A recommendation based on the different source types and behavior that are used in the included studies is to conduct analyses of the sound environment in a broader variety of typical workplaces. Reliable data on the actual sound environment can serve as input for laboratory experiments [55].

In the included studies, sound is considered to be either a distractor, or an essential part of the task. This clear distinction may not always be present in natural work settings. Furthermore, people who are instructed that all sound can be ignored, or informed that sound has a negative influence on performance tend to react differently to sound than people with opposite instructions [56]. In two of the included papers in which sound is not part of the task itself, participants are explicitly told that any sound is task-irrelevant and can be ignored [27,33]. Similar instructions are found in studies excluded in the third review round [46,57,58]. This cannot be compared to a realistic work environment in which speech from colleagues may also be directed at you. In some specific settings, shielding yourself from any external stimuli might even be detrimental to work performance. An obvious example can be found in nursing, in which it is important for patient safety to be constantly aware of the environment, but also for a teacher, a factory employee, a restaurant waiter and for an office employee it is not always possible to ignore the auditory environment. An important consideration for future studies is to investigate and include the role of the sound environment for the specific task or job.

4.2.2. *Space typologies*

The space typologies that are represented by the included studies are two open-plan offices (size unknown), a 18 m^2 classroom, a medium sized, almost square office of around 80 m^2 and sound attenuated laboratory booths. As the effect of room acoustic design on the sound environment becomes more pronounced with increasing distance between source and receiver [33], its effect on human performance in environments with larger distances between distracting sources or different shapes, such as long corridors can be expected to be more pronounced as well. The limited amount of evidence on a broader variety of space typologies and their use could be addressed in future research.

4.2.3. *Task types*

To assess the effect of sound on task performance the ability requirements approach has been introduced as a potentially useful taxonomy by Fleishman [59]. This approach centers around the idea that certain abilities are required for maximum performance of certain tasks. Some examples of abilities are memorization, mathematical reasoning, information ordering, control precision and reaction time. Tasks that require similar abilities can be placed in the same category or can be regarded as similar. The effect of room acoustics on a task could then be expected to be seen similarly on other tasks requiring similar abilities. In 16 out of 24 included experiments [27,30,32,33,36–38,43,45] the effect of acoustics on a task designed to measure an ability are presented. Recall of visually or aurally presented items, for example, is a commonly used performance measure to assess memorization. While the importance of memorization or other abilities in various job settings should not be underestimated, the effect of room acoustics on an ability cannot be generalized to complex task performance, let alone to job performance. The results of these experiments are useful in acoustic design if an analysis of the required abilities for the job that is to be performed is available. Proofreading [30], text memory (auditory and visually) [33,39], text typing [30] and comprehension of a classroom learning task [44] are the complex tasks for which an effect of room acoustics, given a certain sound environment, is reported in this review. These experiments are closer related to a task in the natural working environment.

The included studies, with exception of [40], focus on a task or ability and not on the characterization of a job that is performed in a specific area. While measuring abilities and complex tasks might tell us something about a small part of the job, operationalizing the full process of complex tasks is a necessary next step [60]. For future studies aiming to establish the effect of room acoustics in a certain environment, this means to not exclusively look at the performance of each task, but take into account the planning, prioritizing and executing (or not) of the consecutive tasks as well. Furthermore, job performance, defined as the overall expected value from employees' behaviors carried out over the course of a set period of time [61], comprises both task performance and contextual performance. Contextual performance refers to a behavioral aspect which cannot be measured in laboratory experiments aimed at direct results. Examples of behavior that fit under the umbrella of contextual performance are helping out a colleague or creating a positive social atmosphere in a department. Subjective evaluations of performance such as conducted by Seddigh et al. [40], or studies on psychosocial aspects such as [62] could provide more insight on contextual performance. The scope of the current work did not include the psycho-social aspects of the working environment as a performance indicator however.

4.2.4. Personal factors

From the results in Table 2 it can be read that most studies are conducted with young adults or students, the age range is 19–45. The included field study [40] does not report the age of the subjects, but given the fact that the study is conducted in an office environment it is expected that a mixture of the working population age is represented. Addressing older age groups in future studies seems a logical step considering the ageing workforce [63], and the fact that age has an effect on our hearing ability. Working memory capacity (WMC) [36,39] and noise sensitivity [33] are the only personal factors moderating the effect of room acoustics on human performance identified in this review. Although every individual will differ in its way of reacting to the environment, workplaces are generally built to be suitable for a group of workers. To determine the effect of room acoustics on job performance for a group of people performing the same job in the same sound environment, establishing personality traits by means of questionnaires or other available data available on the personalities of a certain population can improve future studies. Literature on the moderating effect of personal factors, such as [64] can be used to determine which factors to control for. In the design of experiments, subjects should be selected that represent the population under study.

4.2.5. Other environmental factors

It can be seen from both the included as the excluded material that there are very few studies in which the auditory conditions are congruent with the other sensory conditions. In these cases, recorded sound is presented through speakers or headphones in a sound attenuated booth or a laboratory. In natural working conditions the auditory environment is a result of activities in a room. Working on a task in an isolated booth while hearing typical office sounds could be considered unnatural [65,66]. Whether the visibility of sound sources is of importance for the amount of performance decrement could be investigated in future studies.

4.3. Inclusions after the second review round

The results of the second review round show that there are over 250 studies showing the effect of sound and noise on human performance. Studies in which moderate level differences of 10–30 dB have been used indicate that combining acoustical interventions with other noise reduction strategies may lead to positive outcomes. Despite the fact that from these studies the role of room acoustics is unclear, they are useful for determining in which situations the role of acoustics can be expected to be significant. The 259 references that fully complied with the 2nd round inclusion criteria and of which full text copies could be obtained might be of value for other research purposes and they are therefore included [9–11,16,26,46–49,51,57,58,67–313]. They are marked with an asterisk in the reference section.

5. Study limitations

The search terms included terms relating to the work environment to limit the amount of papers which possibly increased the risk of missed papers. The inclusion of papers which were not identified through the search strategy confirms this risk.

6. Conclusion

The main objective of this review is to answer the question to what extent the current knowledge on the effects of sound on human performance can be used to identify the role of room acoustics. Only a small proportion of the available studies measuring the effect of sound on human performance can be used, and the generalizability of these studies is limited to settings in which source type, sound-task interaction, room type, task type and personal factors are similar to the experimental settings. To show how these aspects relate to the effect of room acoustics on human performance a conceptual model is suggested. The distinction between the effect of sound on human performance and the effect of room acoustics on the sound environment is an important aspect of the model, ignoring it could lead to overestimating the role of room acoustics. Furthermore, translating the outcomes of studies measuring the effect of sound on human performance to the role of room acoustics directly, without taking all the factors in the conceptual model into account could lead to wrong assumptions.

Room acoustic design can be a strategy to control the sound environment in a workplace. However, evidence regarding the effectiveness of this strategy with respect to human task performance is lacking and should be a focus area in future studies. The present review presents those combinations of source characteristics, room typology, job or task characteristics and personal factors for which an effect of room acoustics on performance has been established. It can be concluded that little knowledge is available. Even more so, it shows the complexity of measuring the effect of room acoustics on job performance for the various types of workplaces and the typical jobs that are performed.

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