Review of research on the effects of noise on cognitive performance 2014-2017

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ABSTRACT

A literature review was conducted covering the years 2014 to 2017 with a focus on the methods used to study the effects of noise on cognitive performance. *Sound* or *noise* and *cognitive performance* as well as several synonymous or related terms were used in the search string. The search resulted in a total of 1114 posts which were reduced by keeping only those publications that were work-related. This resulted in 82 articles. After a practical screen of the abstracts 47 publications still remained relevant. Several studies aimed to investigate the effects of office noise and addressed either only main effects of noise and/or interaction effects with other parameters, such as ventilation parameters or odors. Some studies extended the focus to the effects of noise in different office types. In this context noise abatement measures, like sound masking, were also tested. Furthermore, some studies dealt with the positive effects of sound by means of its restorative potential. Besides the more applied research work, several basic research studies were found dealing with the irrelevant sound effect and tests of different tasks and outcome measures of cognitive performance, such as mathematics, reading, word processing and writing.

LITERATURE SEARCH

A literature search was conducted covering the years 2014 to 2017. The search string was designed without truncations but with phrases. The searches were conducted within titles, abstracts and keywords in Scopus and Web of Science. Additionally a free text search on the mentioned phrases in PsychInfo and Academic Search Elite was performed to complement with additional articles. The search string in Scopus and Web of Science is shown below:

((Noise OR Sound) AND ("Cognitive performance" OR "Cognitive work" OR "Cognitive processing" OR "Cognitive activity" OR "Cognitive ability" OR "Cognitive task" OR "Mental work" OR "Mental task" OR "Mental processing" OR "Memory task" OR "Working memory" OR "Executive function" OR "Attentional focus" OR "Attentional capture" OR "Problem solving") AND (Work OR Job))

The searches resulted in a total of 1114 posts, which were reduced by including only (limit to) those publications including the following terms and phrases: offic*, "work env*", workplace*,

"work task", job, "work perfo*", as well as "work-related", which could also be expressed with Boolean operators. A limitation was made in order to retrieve papers which included one of the following terms and phrases: offic* OR "work env*" OR workplace* OR "work task" OR job OR "work perfo*" OR "work-related". This resulted in 82 articles. Next the abstracts were practically screened according to the relevance of their content and 47 publications were included in the final qualitative review.

LITERATURE REVIEW

Research dealing with the effects of noise on performance and behavior suffers from the fact that a variety of independent and dependent variables are investigated. Therefore the comparability of the results often is not given. However, during the past years some homogeneity with regard to the used methods can be observed. A short overview of the different independent and dependent variables is given below. Following that, the independent and dependent variables as well as the results of the studies are summarized in tabular form. It appeared reasonable to separate between studies with a rather applied research perspective as compared to rather basic research studies. However, this separation is arbitrary.

Independent variables

Sound Quality

The qualitative review showed that the studies from the last four years were dealing with many qualitatively different sounds (see Table 1 and Table 2). This includes intelligible speech or unintelligible speech, technical sounds like sound emissions of printers or telephone ringing, natural sounds, a urban sounds and/or traffic sounds [e.g. 1, 10, 12, 15, 16]. Additionally, silence was mostly included as a reference condition.

Speech Intelligibility

Several of the studies included in this review showed an interest in the effects of speech intelligibility on task performance, with a focus on comparisons of sounds with different intelligibility (see Table 1 and Table 2). Intelligibility was either operationalized qualitatively or by means of physical parameters like the Speech Transmission Index (STI) or STIt [e.g 1, 4, 5, 8]. STIt is an average of the sliding STI-values calculated over a short time window. Additionally room acoustical measures which are related to the STI [e.g. 7] were investigated. For example, the spatial decay rate of speech ($D_{2,S}$), describes to what extent the level of A-weighted speech is reduced when the distance to the speaker is doubled. The speech level at 4 m distance ($L_{A,S,4m}$) describes the A-weighted level of speech at a distance of 4 m from the speaker. The distraction distance (r_D) describes the distance where STI drops below 0.50. Reverberation time (T_{60}) is the time during which the sound level decreases by 60 dB after the sound source has ceased to operate. The Weighted Sound Reduction Index (R'_w) is a single number rating of airborne sound insulation between rooms. Fluctuation Strength (F), which is a measure of slow modulations regarding to frequency or amplitude (fmod < 20 Hz), is not a direct measure of speech intelligibility. However, this measure is mentioned here since one of the physical features of speech is its high fluctuation strength [e.g. 16]. Also reported or manipulated is the signal to noise ratio (SNR) between speech and background sound which impacts on speech intelligibility [e.g. 33].

Level

Effects of different sound pressure levels were not in focus within the reviewed literature (see Table 1 and Table 2). If the level was investigated, usually the A-weighted equivalent sound level (L_{Aeq}) or the A-weighted equivalent sound level referring to a certain time of integration, for example 8 hours (L_{Aeq8h}) was reported [e.g. 7, 8]. The equivalent sound level refers to the level of a continuous sound with the same energy as a variable sound during the defined period of time. Sometimes also the A-weighted maximum sound level (L_{Amax}) or a statistical sound level (e.g. L10) was reported [e.g. 22]. The statistical sound level refers to a sound level that exists or is exceeded during a defined percentage (e.g. 10%) of the measurement time.

Office-Type

Some of the studies included in this qualitative review compared different office-types with regard to their effects on different outcome measures [e.g. 2, 3]. These studies did not primarily focus on noise effects but are reported here since differences in background noise are discussed to be one of the potential reasons for the observed effects. The office-types investigated included cell-offices, shared-room offices, small, medium-sized and large open-plan offices, as well as flex-offices and combi-offices. In one study [7] the effects of an office refurbishment were investigated by a comparison of a pre- and post-refurbishment questionnaire.

Dependent variables

Performance

A variety of different measures of performance was used in the reported literature (see Table 1 and Table 2). Those measures include working memory tasks, like digit span, word recall, reading span, backward digit span, operation span and the N-back task. Often, the serial recall paradigm is applied which puts special emphasis on the correct repetition of the order of the task items. However, also tasks focusing on cognitive functions different from or only partly relying on working memory were applied. These tasks for example include the attention network task or functional field of view task, as well as tasks for text memory, prose recall, proof reading, text production, mental arithmetic, counting, word categorization, orthographic and phonological decoding, lexical decision-making, rhyme-judgment, executive functions, psychomotor speed or visual attention. In particular, the keep track task, the sustained attention to response test, the number-letter task, the Bergen Right Left Discrimination Test, the Stroop Test, the so called Simulated Combat Control System and an information extraction task were also applied in the reported studies. Additionally questionnaires were used which asked for perceived performance or for items assumed to be related to performance, like perceived work interruptions.

Task-Load

Many studies investigated perceived task-load (see Table 1 and Table 2) which is usually measured by the *NASA Task Load Index* (NASA-TLX), but the usage of a visual analogue scale is also reported [e.g. 12].

Annoyance

Different rating scales were used to measure perceived annoyance (see Table 1 and Table 2). Mostly 5-point rating scales or 7-point rating scales were applied. Often rating scales referring to ISO/TS 15666, which corresponds to the recommendations given by ICBEN [0], were used.

Perceived disturbance

In one study [5] perceived disturbance was measured by the mean of three 5-point rating scales, which addressed the easiness to habituate to the sound environment, the pleasantness of the sound environment and the impeded ability to concentrate. In another study disturbance by different sounds was measured by 13 items on a 5-point rating scale [7]. The Borg CR-10 scale was also used [10, 11].

Mood

Mood was measured by the Positive and Negative Affect Schedule, which is a 5-point Likert scale [29]. The use of the Zuckerman Inventory of Personal Reactions and Feelings or the Maslach Burnout Inventory (MBI-GS) was also reported [27].

Leadership

As an example, leadership was measured by the global leadership and organizational behaviour effectiveness program (GLOBE). The modern work life questionnaire, which measures employees' perception of leadership by two questions, was also applied. Additionally the use of the leadership scale from the stress profile was reported which consists of ten items that describe aspects of the employees' relationship with the manager [2].

Health

Health was operationalized by the sick leave rate or by health symptoms. The sick leave rate was reported by the participants and subdivided into short and long (medically certified) sick leave spells. The total number of sick leave days was also investigated [2,3]. Additionally health symptoms like headache or eye symptoms were asked for [e.g. 7]. The use of the Swedish Occupational Fatigue Inventory was also reported [27].

Job Satisfaction

Job satisfaction was investigated by questionnaires and usually a 5-point rating scale was used [e.g. 7]. Some studies separated between psychological demands at work and social support between colleagues at work and descriptive factors of work, like decision authority and skill discretion in employees' work assignments.

The following tabular overview is not supposed be complete, since some studies apply very large questionnaires even so not all variables are analysed and reported within those studies.

Applied Research Studies

Table 1: Overview of Applied Research Studies

Author	[1] (Brocolini et al. 2016)	[2] (Danielsson 2016)	[3] (Danielsson et al. 2014)	[4] (Ebissou et al. 2015)	[5] (Haapakangas et al. 2014)
Result	Intelligibility affects performance. Higher vulnerability for subjects with lower capacity.	Overall results show that shared-room office, traditional open plan offices and flex-office stand out negatively, but to different degree(s) on the different measured outcomes.	Increased risk of short term sick leave in open-plan offices. Gender effects occur.	Higher intelligibility yields stronger impairment of performance and task load. Effects of capacity occur.	Speech disturbs performance. Room acoustical measures hardly provide relief from impairment of performance but disturbance is less. Noise sensitive participants perform worse.
Sound quality	ventilation sound, printers, intelligible speech, unintelligible speech				
Speech Intelligibility	STI, STIt			STI	STI
Level					
Office Type		cell-, flex-, combi-, shared-room office, small, medium, large open-plan office	cell-, flex-, combi-, shared-room office, small, medium, large open-plan office		
Performance	word recall			digit span	digit span, operation span, N-back task, text memory
Task Load	NASA-TLX			NASA-TLX	NASA-TLX
Annoyance	5-point rating scale				
Distraction					
Perceived Disturbance					5-point rating scale
Mood					
Leadership		leadership scale of the stress profile and GLOBE			
Health		short, long and total sick leave	short, long and total sick leave		
Job Satisfaction					
Environmental Satisfaction					
Moderator	capacity	gender	gender	capacity	noise sensitivity, capacity

[6] (Hodgetts et al. 2014)	[7] (Hongisto et al. 2016a)	[8] (Hongisto et al. 2016b)	[9] (Hua et al. 2015)	[10] (Hua et al. 2014a)	[11] (Hua et al. 2014b)
Task resumption is prolonged by background sound and workload is increased.	Environmental and job satisfaction improves after refurbishment of an office. Effects are multicausal.	High sound insulation between adjacent rooms yields positive effects on performance and well-being.	Semi-structured interviews identify noise at work to facilitate problems of employees with moderate hearing impairment. Room acoustic measures provide some relief.	No effect of noise on performance but on perceived disturbance. Disturbance relates to noise level. No difference between hearing impaired and healthy subjects.	No effect of noise on performance but on perceived effort. No difference between hearing impaired and healthy subjects.
silence, speech				silence, office noise, daycare noise and traffic noise	silence, traffic noise
	$D_{2,S}$, $L_{A,S,4m}$, r_d	STI			
	L_{Aeq8h}	L_{Aeq}		L_{Aeq}	
	pre-post office refurbishment				
Simulated Combat Control System (decision making-, resumption time)	5-point rating scale, perceived peace for work, interruption frequency	digit span, mental arithmetic, text production, 5-point rating scale		mental arithmetic, orthographic and phonological decoding, serial recall	lexical decision-, rhyme-judgment-, reading span-, sustained attention to response test, keep track-, number-letter-, information extraction task
NASA-TLX		NASA-TLX			
	5-point rating scale, 8 items for distraction by different sounds	5-point rating scale			
	5-point rating scale, 13 items for disturbance by environmental parameters			Borg CR-10 scale	Borg CR-10
		7-point rating scale, valence and arousal			
	5-point rating scale, health symptoms like headache, stress, eye symptoms	stress			
	5-point rating scale				
	7-point rating scale	5-point rating scale, acoustic satisfaction			
				moderate hearing impairment	moderate hearing impairment

[12] (Irgens-Hansen et al. 2015)	[13] (Jahncke et al. 2016)	[14] (Lamb und Kwok 2016)	[15] (Lambert et al. 2014)	[16] (Liebl et al. 2016)	[17] (McKinley et al. 2015)
Effect of higher noise exposure on reaction time only occurs if age, alertness, work load, noise exposure in test location, sleep the night before, wearing hearing protection and percentage of errors is controlled.	Masking speech with nature sound improves performance. Perceived workload is lowest during silence.	Environmental stressors act indirectly on work performance by reducing state variables, motivation, tiredness, and distractibility. They also adversely affect well-being.	No effect of different aircraft sounds on performance. Lowering of the number of aircraft movements reduces annoyance even at same levels.	Speech impairs performance more than all other sound conditions and variable speech-like noise is more impairing than continuous speech-like noise. Sound masking with continuous speech-like noise provides relief from the negative effect of background speech.	Cognitive distraction impairs performance but auditory distraction does not.
ship noise	silence,1 voice (with or without headphones and masking by nature sound or 7 voices)		reference-, halved number-, modified quality aircraft sound	silence, pink noise, continuous speech-like noise, variable speech like noise, masked speech, speech	silence, continuous ambient ward noise
	STI			STI, F	
L_{Aeq}					
		data from employees in 66 different office buildings			
visual attention test	digit span	11-point rating scale, Stroop Test	word list memory task, Stroop Test	digit span	Bergen Right-Left Discrimination Test
visual analogue scale	NASA-TLX				
		ICBEN	ICBEN	ICBEN	
		11-point rating scale			
			5-point rating scale		
		11-point rating scale			
		symptoms, Karolinska Scale, medication			
age, alertness, workload, sleep, noise at test location			noise sensitivity, evaluation of and attitude towards source		age, sex and handedness

[18] (Molesworth et al. 2014)	[19] (Molesworth et al. 2015)	[20] (Ng 2016)	[21] (Roer et al. 2014)	[22] (Sala und Rantala 2016)
Simulated aircraft noise impairs performance of nonnative English speakers more than the performance of native English speakers. Noise cancelling headphones help to improve performance for nonnative speakers only if audio is played through the headphones.	Simulated aircraft noise impairs recognition memory but not working memory or reaction time. The effects are more pronounced for non-native speakers.	Review concludes that mobile workers in public and semi-public spaces are negatively affected by the physical (e.g. noise) and social characteristics of spaces. Planning and coordinating work tasks for different workplaces is time-consuming and requires to overcome obstacles.	Performance is impaired by ringtones but habituation occurs. It doesn´t matter if the ringtone is familiar or not.	Few classrooms fulfill the acoustic criteria for reverberation time of the Finnish national standard and no classroom fulfills the STI criterion. In most of the classrooms the background noise level is higher than recommended and activity noise levels are high for listening and communication.
speech in noise, active noise cancelling headphones	silence, simulated in-cabin aircraft noise			
				STI,T_{60}, L_{10},L_{50},L_{90};L_{Amax}
			silence, ringtones	background noise level, activity noise level
text memory	recognition memory, working memory, reaction time		digit span	
native language	native language			

[23] (Schlittmeier et al. 2015)	[24] (Schlittmeier und Liebl 2015)	[25] (Seddigh et al. 2015)	[26] (Techera et al. 2016)
Better performance during moderate road traffic noise at 50 dB(A) compared to loud traffic noise at 70 dB(A) in attention-based tasks but only speech impairs performance of working memory based tasks. Additionally annoyance is lowest during silence and high for high level road traffic noise in all tasks but also for speech in the digit span task.	A survey among employees and three experimental studies identify background speech to impair performance and annoyance. Sound masking provides some relief.	In a field study the drop of performance from the quiet baseline compared to normal working conditions is higher in larger, compared to smaller open-plan offices. However, cell-offices perform even worse than large open-plan offices.	A meta-analysis of occupational fatigue identifies sleep deprivation and work environment factors like noise, vibration, and temperature to have the greatest effect sizes.
silence, speech, high density traffic noise at 50, 60, 70 dB(A), low density traffic noise at 60 dB(A)	silence, speech of low and high intelligibility, (continuous noise staccato and legato music as maskers)	cell-office, small, medium, large open-plan office	
		silence, normal office working conditions	
L_{Aeq}	STI, L_{Aeq}		
Stroop Test , mental arithmetic, digit span	digit span	immediate free recall, Attention Network Test	
5-point rating scale			
	ranking of different aspects of the work environment		
		sex, age, labor market sector, educational level and distraction	

[27] (Varjo et al. 2015)	[28] (Zaglauer et al. 2017)
Performance is impaired by a combination of high room temperature, highly intelligible speech and low fresh air supply rate as compared to neutral temperature, speech of low intelligibility and high fresh air supply rate. Mental workload, cognitive fatigue and symptoms are higher and environmental satisfaction is lower for the first combination.	Performance improves and annoyance and measures of subjective workload diminish if background speech is masked by at least six babble voices. However, performance level is far from working during silence.
	background speech, background speech masked by babble
	STI
	L_{Aeq}
serial recall task, operation span task, N-back task, information search task, typing task, story-writing task	digit span
NASA-TLX	NASA-TLX
	ICBEN
Zuckerman Inventory of Personal Reactions and Feelings	
Swedish Occupational Fatigue Inventory	
7-point scale	
noise sensitivity	

Basic Research Studies

Table 2: Overview of Basic Research Studies

Author	[29] (Emfield et al. 2014)	[30] (Halin et al. 2014b)	[31] (Halin et al. 2014a)	[32] (Heald und Nusbaum 2014)	[33] (Hygge et al. 2015)	[34] (Ljung et al. 2015)	[35] (Marsh et al. 2014)
Result	No effect of restorative stimuli on performance but nature sounds are perceived to be more relaxing.	Participants perform better in speech if a demanding task is applied. Capacity only affects performance in the less demanding task.	Participants perform better in speech if a demanding task is applied.	Passive and active concepts of speech perception are discussed which are also relevant for hearing in noise.	Recall of words is impaired more by higher background noise than speech intelligibility. Recall is regarded to be a more suitable set value for the optimization of room acoustics.	Performance in counting is impaired by the meaning of background speech only if the counting task requires spatial memory processes.	Irrelevant speech impairs free recall of semantic category exemplars. Semanticity is of importance. Impairment is greater if speech is semantically related but only if the irrelevant words are high in output dominance.
Sound quality	natural and urban sounds	silence, speech	silence, speech		SNR	silence, speech	silence, forward speech, reversed speech, related speech, unrelated speech
Speech Intelligibility							
Level							
Performance	backward digit span, attention network task, functional field of view task	reading speed, memory for prose	proof reading		word recall, shadowing	counting	word recall
EEG							
Task Load		7-point rating scale	7-point rating scale				
Relaxation	7-point Likert scale						
Task Difficulty		7-point rating scale	7-point rating scale				
Mood	Positive and Negative Affect Schedule						
Moderator					operation span		

[36] (Meinhardt-Injac et al. 2015)	[37] (Moore et al. 2014)	[38] (Okazaki 2014)	[39] (Pelletier et al. 2016)	[40] (Perham et al. 2016)	[41] (Schwarz et al. 2015)	[42] (Sokka et al. 2014)	[43] (Sokka et al. 2016)
Younger children are more sensitive to impairment by background sound. Results suggest that attention distraction and immature attention control mechanisms contribute to the effect of background sound.	Review shows decreasing cognitive ability and increasing age are both independently associated with decreasing ability to hear speech in noise. Workplace noise history is associated with difficulty in hearing.	Office noise and ocean wave combined with odor lead to differences in EEG.	Interference due to irrelevant sound is greater for adults with ADHD.	Performance is best in quiet, worse in a descending numbers condition, and poorest in a ascending numbers condition.	The impairment by background speech is not modulated by task difficulty and the effect ist he same for children and adults.	Tendency in job burnout participants to react faster to negative, and slower to positive information compared to that of control participants.	Task performance is comparable between burnout participants and control group. Data suggests some burnout-related deficits in processing novel and potentially important events during task performance since a decrease in working-memory related electrophysiological responses is observed.
pink noise, foreign speech, classroom sounds		office noise, sound of wave	silence, office noise	silence, background speech (ascending or descending numbers)	pink noise, speech	bisyllabic pseudoword and deviants in emotioal prosody	silence, complex environmental distractor sounds
mental arithmetic, word categorization	fluid Intelligence, prospective memory		letter recall	mental arithmetic	word recall		N-back task
		EEG				EEG	EEG
							Karolinska SleepinessScale
age	age, gender, noise exposure	target tracking task	ADHD		age, task difficulty		

[44] (Sörqvist 2015)	[45] (van de Poll, M. K. und Sorqvist 2016)	[46] (Wright et al. 2014)	[47] (Wright et al. 2016)
The authors demands that cognitive noise researches should employ tasks that mimic the tasks that are actually carried out in the applied setting to which the results are intended to be generalized. Tasks that measure 'sub-component abilities' may be complementary, but should not be given priority in applied cognitive research.	Background speech has only a small effect on performance but a dialogue is more disruptive than a halfalogue. Background speech contributes to perceived workload.	Review reveals that noise impairs attention, working memory and episodic recall and show that personality characteristics, like neuroticism influence the impact of noise stressors on performance in interaction with task complexity	Significantly slower psychomotor speed (urban), reduced working memory and episodic memory (urban and social) and more cautious decision-making (urban) under noise conditions.
	silence, background speech (monologues, halfalogues and dialogues)		quiet, urban, and social
	writing task		psychomotor speed, attention, executive function, working memory, verbal learning memory
	NASA-TLX		
	interruption (secondary task)	schizophrenia	IQ, subjective noise sensitivity, sleep, personality, paranoia, depression, anxiety, stress, schizotypy

CONCLUSION

This review has shown that there is some consistency in relation to the applied measures of performance and behavior used between international groups of researchers. However, it is nonetheless important for these research groups to exchange information concerning the applied methods used and to agree upon some measures to be used as standard. From the applied research studies reviewed, it is evident that the intelligibility of background speech is a predictor of the impairment of task performance, with greater intelligibility giving rise to more pronounced disruption. Similarly, increasing intelligibility of background speech is also associated with greater complaint concerning noise within office settings. Considering the clarity of these findings, it is surprising that political and public authorities react minimally to addressing these negative objective and subjective effects of (particularly intelligible) background speech. The main focus on noise abatement policy is still on reducing sound pressure levels. In this respect, more political engagement would appear to be necessary in order to transfer the implications of the results into practice (e.g., novel policies). It is also important to challenge rather unprofessional and marketing-driven arguments about the positive effects of babble speech and the associated promotion of working in public spaces. These claims that working within noise can have positive effects on cognitive performance

should be addressed with tightly controlled empirical investigations like those reviewed in the current article. The research reviewed here has also shown that typical room and building acoustical measures hardly provide any relief from the impairment of performance. Therefore, research should also focus on developing and providing solutions that help to reduce the impairment of performance. This includes investigations into the generalizability of the results which mainly stem from laboratory research to real workplace settings and real work tasks. To address the potential short-comings of this approach, more field studies are required. Moreover, future studies should address the impact of background speech on the performance on tasks more representative of those undertaken in the work setting than the working memory tasks that have traditionally been used.

There is emerging evidence that individual differences variables moderate the disruption produced by background sound. For example, the literature shows that individuals with lower working memory capacity and poorer speech skills may be more vulnerable to noise effects. It is possible that age is also a factor in these findings. Future research should therefore place more emphasis on the consideration and discovery of moderating and mediating variables as may be found within groups vulnerable to distraction. Parallel with the current trend in investigating the impact of speech with different levels of intelligibility, is another trend with a focus on the role that the semanticity of background speech plays in disrupting cognitive performance. This research considers both the mere effect of semanticity (the presence or not of semantic content within the background speech) and the similarity in semantic content between the background speech and task material in disrupting the performance of an ongoing task.

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