DOCTORAL THESIS

Cognitive Performance and Restoration in Open-Plan Office Noise

Helena Jahncke

LULEÅ UNIVERSITY OF TECHNOLOGY

Dissertation for the degree of Doctor of Philosophy

Cognitive performance and restoration in open-plan office noise

Helena Jahncke

Environmental Psychology
Faculty of Engineering and Sustainable Development
University of Gävle, Sweden

and

Division of Human Work Science
Department of Business Administration, Technology and Social Sciences
Luleå University of Technology, Sweden

The cover picture is from Shutterstock

Printed by Universitetstryckeriet, Luleå 2012

ISSN: 1402-1544
ISBN 978-91-7439-495-5

Luleå 2012

www.ltu.se

Abstract

This dissertation presents four experimental studies (in four papers) with the overall aim to investigate the effects of office noise on cognitive performance and restoration. In the first two papers the focus was on the effects of different sound levels (i.e., the mean level from all sound sources at an office, such as speech, phones, people walking) on performance, fatigue and stress. In the last two papers the focus was on the effects of background speech, as this has previously been shown to be the most disturbing noise source in open-plan offices. Paper I demonstrated decreased word memory performance, increased fatigue and motivational deficits when the background sound level increased by 12 dB, from 39 to 51 dB LAeq. Paper II showed that the sound level effects were more pronounced for individuals with a hearing impairment. Unexpectedly, no effects were found of acute noise exposure on the participant´s stress hormone levels (Paper I and Paper II).

Regarding effects of irrelevant speech, Paper III showed that cognitive performance decreased as a function of background speech intelligibility, the higher the intelligibility depicted by the Speech Transmission Index (STI), the worse the performance. The results indicated that the STI-value must be less than 0.50, to avoid a negative influence on performance. Further, both Paper III and IV showed that performance is more impaired by background speech if the focal task requires episodic memory and rehearsal—such as word memory and information search. Interestingly, some tasks were insensitive for speech.

The restorative effects of a break were addressed in Paper I and II (i.e., directly after the work sessions in noise). The break period differed in content between the participants. Paper I showed that a break with a nature movie with corresponding sound increased energy ratings compared to just listening to river sounds or office noise. Continued exposure to office noise gave the lowest ratings of motivation after the break. Paper II showed improved arithmetic performance and motivation after the break with a nature movie and decreased performance and motivation after continued noise exposure. For the hearing impaired participants, however, continued noise during the break increased motivation and performance, while the movie did not.

Taken together, the current thesis demonstrates that open-plan office noise can have a negative impact on fatigue, motivation and performance. How much performance is impaired varies with the cognitive processes required by the tasks performed and hearing status. Moreover, continued noise exposure during a short break can further decrease motivation and subsequent performance.

List of papers

I. Jahncke, H., Hygge, S., Halin, N., Green, A-M., & Dimberg, K. (2011). Open-plan office noise: cognitive performance and restoration. *Journal of Environmental Psychology*, *31*, 373-382.

II. Jahncke, H., & Halin, N. (2012). Performance, fatigue and stress in open-plan offices: the effects of noise and restoration on hearing impaired and normal hearing individuals. *Noise & Health*. [Accepted]

III. Jahncke, H., Hongisto, V., & Virjonen, P. (2012). Cognitive performance during irrelevant speech: effects of speech intelligibility and office-task characteristics. *Applied Acoustics*. [Accepted]

IV. Jahncke, H. (2012). Open-plan office noise: the susceptibility and suitability of different cognitive tasks for work in the presence of irrelevant speech. *Noise & Health*. [Accepted]

The articles are reprinted with the permission of the publishers.

Table of contents

Acknowledgements 1

Introduction 3

- Aims 3
- Open-plan office noise 4
  - *Recommendations and standards for the acoustic environment* 6
  - *Effects of different noise sources and sound levels on cognitive performance* 7
  - *Effects of noise on fatigue* 8
  - *Effects of noise on stress* 9
  - *Individual differences with focus on hearing status* 10
- Type of task and cognitive activity 11
- Restoration 13
  - *Effects of sounds* 14
  - *Cognitive measures of attention restoration* 15
- Research issues 18

General method 19

- Research settings 19
- Independent variables 19
- Dependent variables 20

Paper I: 22

- Method 22
- Results and discussion 23

Paper II: 24

- Method 24
- Results and discussion 26

Paper III: 27

- Method 27
- Results and discussion 29

Paper IV: 30

- Method 30
- Results and discussion 31

General discussion 32

- Open-plan office noise and some practical implications 32
  - *The burden of noise in open-plan offices* 35

Restoration and some practical implications 36
Methodological limitations 37
Future research directions 38
Funding body 39
Svensk sammanfattning 40
References 41

Acknowledgements

There are many people who have supported me in the completion of this work to whom I would like to express my sincere gratitude, in particular:

I am heartily grateful to my supervisor Professor Staffan Hygge, for the bright scientific guidance, endless support and personal care he has given me over these years. He helped me take steps which I never thought I could take.

I am also very thankful to Niklas Halin, my research collaborator and friend, for all assistance and contributions to this project. I am impressed that he held out despite the late nights with experiments, and biological samples which were not always the most pleasant to take care of.

This journey would never have been the same without my dear colleagues within the research group of Environmental psychology. I would especially like to thank Robert Ljung och Patrik Sörqvist for their exceptional support over all these years. I could "never, never, never give up" when I had them around.

I am also grateful to Professor Terry Hartig, my supervisor at the undergraduate level, without whose encouragement I would not have considered a PhD student position. Despite a busy calendar he has continued to provide me with helpful advice, support, and comments on numerous manuscripts and he is today an invaluable mentor and friend.

I also wish to thank Professor Anders Kjellberg and Dr. John Marsh whose insights and comments have been invaluable throughout this work.

Further, I would like to thank Dr. Johan Odelius and Dr. Örjan Johansson, for their acoustic guidance and all help with the recordings and arrangements for the sound settings. Thanks also to all lab-engineers, particularly Dr. Claes Blomqvist, Rangvald Pelttari and Rickard Larsson for help with the simulated open-plan office.

Appreciations also go to Professor Håkan Alm, my supervisor at Luleå University of Technology, for all administrative help, Professor Stig Arlinger for helpful comments on an earlier draft of this thesis, and Anne Marie Green for her very proficient introduction of me into this new research field.

I would also like to thank all my colleagues at Fraunhofer Institute for Building Physics, Stuttgart and at Finnish Institute of Occupational Health, Turku, for the valuable knowledge exchange and the opportunities provided to me as a guest researcher.

I would also like to express my gratitude to my colleagues Elisabet, Ebbe, Setareh, Shahriar, Huijuan, Amir, and their respective partners, who helped make my PhD time more fun and interesting also outside work.

My dear friends Cilla, Mariam, and my brother, thanks for always being there.

Most of all and with all my heart I would like to thank Mum and Dad for their endless love and support.

Finally, Robert, I am forever thankful that you have come into my life with so much love and a great sense of humor, ready to share the adventures of life with me.

Introduction

Aims

The present dissertation presents the results of four experimental studies, each of which is presented in a paper. The specific aims with the experimental studies are as follows:

1. To assess the acute effects of office sound levels on cognitive performance, fatigue and stress.

2. To investigate whether the magnitudes of these effects vary with hearing impairment.

3. To more closely specify the function between the intelligibility of background speech and performance on different foreground cognitive tasks and to examine how this function varies with the characteristics of the tasks.

4. To explore how different sound conditions in an interpolated break period affect subsequent restoration and recovery in cognitive performance, fatigue, and motivation.

Papers I and II cover the first two aims. Papers III and IV are mainly devoted to the third aim, and the fourth aim is mainly covered in Papers I and II.

Papers I and II are experimental studies of people in a simulated open-plan office setting, and they have a more applied focus. Papers III and IV are closer to basic research in their attempts to compare several acoustical conditions and relate them to different cognitive tasks with different characteristics.

Open-plan office noise

For many people in the Western world the office environment is one of the most important environments of life as the major part of the day is spent there. The layout of the office environment has changed over time with different trends in society (for a review see Danielsson, 2010). There have been several shifts in whether cell-offices (i.e., private office) or open-plan offices (i.e., shared office) have been the most favored office type, ever since the open-plan offices were first introduced at the beginning of the 20th century by Frank Lloyd Wright. After some periods of decline, open-plan offices are again on the increase in Sweden and other parts of the world.

A big survey study in Sweden (Danielsson, 2010) showed that the office type has significance for employee health status and job satisfaction. The employees in cell-offices were the most satisfied with their office environments and were most likely to be in good health, while the employees of small (4-9 persons/room) and medium-sized (10-24 persons/room) open-plan offices had the highest risks for poor health and well-being. Moreover, medium-sized and large open-plan offices (25 < persons/room) were classified as high-risk office types, because of the low satisfaction experienced in this work environment. Poor work environments increase the risk for illness and sick-leaves, which cause high costs to companies and society (Milczarek, Schneider & González, 2009). It is therefore essential to consider the gains and/or costs when changing between a cell-office and an open-plan office.

Arguments for companies to switch from cell offices to open-plan offices include facilitation of the employees' communication and creativity. There is, however, no clear scientific support for such hopes. Probably, the main reasons behind the decisions are the possibility to save money, by making it possible to reduce the office area. Another reason may be the increased control over the workers offered by the open-plan office. Several studies have shown that a cost of moving to an open-plan office is a poorer acoustic environment (e.g., Sundstrom, Town, Rice, Osborn & Brill, 1994). However, little is known how much a deprived acoustic environment influence actual performance and stress. Some acute effects of office noise may show up directly (i.e., irritation, problems to concentrate, impaired performance), while others may show up in the long run, as chronic or more indirect effects (i.e., fatigue, stress and burnout symptoms), which at the end might counteract the beneficial effects. However, in the present thesis merely the acute effects of office noise will be addressed.

It is, however, not easy to assess how disturbing the increased office noise will become for the employees. There are several critical factors to consider just with regard to the

physical properties of sounds. Significant acoustic factors are, for instance, sound level, variability, reverberation time, and intelligibility.

Noise is measured in decibels (dB) and dBA is the most commonly used measure (i.e., the A-weighted level) which means that the sound is measured in a manner similar to how the human ear perceives sound. The equivalent sound level (*Leq*) means a kind of average sound level over a specified period (Johansson, 2002). When the sound level (dBA) is increased with 10 dB in the frequency range around 1000 Hz, the perceived loudness of the sound is doubled. The lower the frequency the greater is the effect of a change in level. Analyses on the relationship between sound level and annoyance consistently show low correlations between individual exposure levels and annoyance ratings, which indicate that there are more factors than just the sound level in dBA that affect perceived annoyance (Landström, 1999).

Another factor of importance is how much a sound is varying over time. Several studies have shown that temporal variability generally increases the annoyance response when compared to continuous sounds (for a review see Kjellberg and Landström, 1994). Kjellberg and Landström argued that one reason might be that constant sounds are more predictable than unexpected sounds and when noise is predictable it should be less annoying than when it is unpredictable.

Furthermore, even though a source stops emitting sounds, its reflections (i.e., echoes) still can be disturbing when a message from another speaker needs to be heard. Research has also shown that even though a message is heard under circumstances where it is a long reverberation time, it will be comprehended and remembered to a less degree (Ljung & Kjellberg, 2009). This is problematic, for example, when an employee needs to hear a conversation with a costumer over phone and other voices in the surrounding are reflected. How fast a sound decays is dependent on the room volume and the room absorption (i.e., the more absorption in the room - the shorter the reverberation time) and an acoustic measure of reverberation time can be used to describe the temporal decay in amplitude (Johansson, 2002). In open-plan offices, however, there are also situations when a long reverberation time is useful as it may help to mask unwanted speech. As the negative effects of speech will grow with increased intelligibility there is a design problem in balancing a reduction in sound level at the same time as not providing too much absorption (the effects of intelligible speech on performance will be discussed in more details later on).

There are, however, also other factors than the physical properties that are decisive for how disturbing a sound is. Some of them are: which tasks the sound interferes with, individual differences (e.g., hearing status, working memory capacity), information content,

predictability and controllability, attitude towards the noise source, personal goals and perceived ability to avoid or mitigate the noise (see Kjellberg, 1999).

In this thesis I studied in more detail the following of these independent variables: sound level, speech intelligibility (see "The acoustic environment"), ongoing activity (see "Type of task and cognitive activity"), and hearing status (see "Individual differences with focus on hearing status"). To start with it is central to know which recommendations that already exists in Sweden according to office noise and then succeed to the research field to understand the effects and the current stage.

Recommendations and standards for the acoustic environment

According to the Swedish recommendations from the Swedish Work Environment Authority the background sound level should not exceed 35-40 dB when work requiring concentration is performed (Arbetsmiljöverket 2005:16). However, in these recommendations the focus is on the building, installations and equipment and does not account for activity sounds in the room. These recommendations are therefore not usable for open-plan offices where most of the sounds stem from the activities in the office. Such sounds are only mentioned in one paragraph, telling that irrelevant speech in an office environment may also be a disadvantage, especially in open-plan offices. Therefore, it is stated that the acoustic design of such facilities should receive special attention. However, in what way this should be done is not told.

Speech sounds are one of the most disturbing noise sources in open-plan offices (e.g., Sundstrom et al., 1994). Hongisto (2005) has developed a model which predicts the loss of work performance as a function of the Speech Transmission Index (STI). STI is a measure of the intelligibility of speech (i.e., the possibility to hear what is said). This measure is dependent of the size of the room, the background sound level and the reverberation time. Speech is perfectly intelligible when STI reaches 1.0 and completely non-intelligible when STI is 0.0. The model that Hongisto has developed is based on a review of a limited number of experimental studies in which cognitive performance has been investigated in different speech conditions. According to the model, task performance will start to decline when STI exceeds 0.2 and the largest decline will be reached above 0.5. This model has been applied in a newly published international room acoustic measurement standard for open-plan offices (ISO standard 3382-3) but not yet into the Swedish standard (SS 25268). These standards also give further methods for the assessment of noise in open-plan offices. Nonetheless, there is still a need to develop the target values of STI and to test a wider array of cognitive tasks than was originally included in the review by Hongisto (2005). Supplementary, it is important to

note that it is difficult to give recommendations which apply to all offices. Researchers on open-plan office noise have to deal with the problems of which sounds and tasks to address to give a good base for the recommendations and future standards.

Effects of different noise sources and sound levels on cognitive performance

There have been different types of sounds in focus when testing the effect of irrelevant sound on performance (for a review see Szalma & Hancock, 2011). Research with focus on combined sound sources has often used the overall sound level (the equivalent sound level, Leq) to test the effect on performance. There are studies showing that performance is reduced by sound levels between 40-76 dBA but not by lower levels around 20 dBA (Colle, 1980), while other studies have found no difference in performance between 60 dBA and 75 dBA overall level (e.g., Ellermeier & Hellbrück, 1998). A common level in open-plan offices is around 50 dBA (Venetjoki et al., 2006). Whether performance is reduced between 20 dB and 60 dB is unclear and will be addressed within this thesis. However, it should be noted that Leq is a blunt measure that does not really take into account the source, or that speech is a very special sound characteristic.

In open-plan offices there is a balancing act between the wish to hear the talk from one colleague (e.g., someone involved in the same project) but not from another (e.g., someone with other work tasks). High speech intelligibility may therefore be good for an ongoing conversation but may also make irrelevant speech more disturbing. Studies with a specific focus on speech sounds have shown that the more intelligible the background speech is - the lower the performance (e.g., Hongisto, 2005). However, the function between the intelligibility of speech and performance need to be further specified, both with respect to target levels and different tasks. The theories behind the irrelevant speech effects will be further discussed in the section "*Type of task and cognitive activity*".

In addition to speech sounds, telephone signals have proved to be a source of distraction. For example, Shelton, Elliott, Lynn and Exner (2009) have in a series of experiments showed that performance (response time in a lexical decision task) was negatively affected by a variety of phone sounds, compared to when no sound was heard. The type of the sound (i.e., a normal phone ring, a song, or tones) showed to affect the time course of the disruption. The ring tone consisting of a familiar song gave the longest-lasting effect on performance, followed in the order of a normal phone ring and tones. The authors argued that the distractions caused by the ring tones can be explained by an involuntary attention

orienting response, which lasts for different lengths of time depending on how it is further top-down processed by the individual.

Another sound source that many employees might not think of until it is turned off, is the low frequency noise produced by the ventilation system. For example, Kjellberg and Wide (1988) showed in an experiment that the participants exposed to ventilation noise had a slower learning rate, and that the errors in a reasoning task was immediately reduced when the noise was turned off, compared to a control group. The control group had the noise turned on at the same point of time as it was turned off for the experimental group. Furthermore, Bengtsson (2003) has conducted a set of studies which showed that cognitive performance is impaired by low frequency noise, and these effects were shown to be influenced by workload and noise sensitivity. More precisely, performance in tasks with high and moderate demands on cognitive processing was impaired by low frequency noise under high workload, while performance in tasks with moderate to low demands was impaired under low workload. The effects were also more prominent for participants high-sensitive to low frequency noise or noise in general. These results are of particular relevance for open-plan offices as ventilation noise (or artificial low-frequency noise) sometimes is used to mask speech sounds (i.e., decrease speech intelligibility), which will be further addressed in the general discussion.

Effects of noise on fatigue

Employees will naturally get fatigued over the day by their work tasks, but factors in the physical environment can also add to this fatigue. According to Kjellberg, Muhr and Sköldström (1998) there are at least three ways in which noise may have fatiguing effects. First, the employees may get overstimulated by noise sources in the background, second, monotonous noise, such as ventilation noise, has shown to elicit sleepiness, and third, it can be more difficult and tiring to perform tasks in noise, as for instance when sudden sounds capture attention away from the focal task. When employees become fatigued, it has significance for their well-being, but also their productivity, their propensity to commit errors and in some professions, for the risk of accidents.

There are some field studies which support the notion that noise may contribute to the fatigue caused by a working day. Melamed and Bruhis (1996) studied workers in a textile factory and found higher subjective tiredness after work without hearing protection (at a sound level of 85-95 dBA Leq), compared to a week when the workers wore hearing protection. Further, Kjellberg, Muhr and Sköldström (1998) performed three independent field studies on airplane mechanics and crews of ships in the coastal fleet. The overall results

showed an increase of reaction times (a simple reaction time test to squares on a screen) from the morning till the afternoon during days of high noise exposure. In the studies of airplane mechanics, it was also shown that the effect of exposure to high sound levels may cause a cumulative effect of fatigue over the working week. In addition, there are some laboratory studies which have demonstrated decreased performance after work in noise, even if no effect of noise was detected during the exposure (e.g., Glass & Singer, 1972).

It is not, however, well established how fatigue should be defined and measured objectively. Fatigue has, for example, been represented by measures of alertness (via EEG) and changes in heart rate and blood pressure. For instance, Landström, Byström and Nordström (1985) indicated a reduction in wakefulness, measured with EEG, during exposure to low frequency noise. This could be considered relevant also with regard to ventilation noise exposure in open-plan offices. Fatigue has not, however, been well documented with cognitive measures. This might be due to the fact that a reduction in performance may not be a mere indication of fatigue (Åhsberg, Gamberale & Kjellberg, 1995). For example, a decrease in performance may as well show a decrease in motivation.

In this thesis I applied the questionnaire developed by Åhsberg et al. (1995), in which five separate subjective dimensions of fatigue (i.e., lack of energy, physical exertion, physical discomfort, sleepiness and lack of motivation) have been defined for studies of mental and physical workload. I also applied some cognitive measures at several stages throughout the experimental procedures to obtain an indication of how performance changed over time.

Effects of noise on stress

There are also some studies directly related to office noise and stress. For example, one study showed that a three hour exposure to low-intensity office noise induced a small increase in adrenaline level, compared to a control condition (Evans & Johnson, 2000). Another study showed that the participants who were highly sensitive to noise in general maintained higher cortisol levels relative to mean base values during a test session of two hours with low frequency noise, compared to low sensitive persons (Persson-Waye, Bengtsson, Rylander, Hucklebridege, Evans & Clow, 2002). However, Kristiansen and colleagues (2008) showed that cognitively demanding work for 35 minutes in simulated open-plan office noise only increased ratings of perceived cognitive effort but not the physiological stress reactions. Sometimes the effects of noise on physiological stress fail to appear because the participants experience control over the noise (Lundberg & Frankenhaeuser, 1978) or there is an absence of effort (Tafalla and Evans, 1997). There might also be several other reasons, such as strong

circadian and weekly rhythms of hormone excretion, which blur the noise effects and to short observation periods (Babisch, 2003). Therefore results regarding the acute effects of office noise on stress hormones have been inconsistent.

The aim of the current thesis was to further test whether psychophysiological reactions mediate declines in cognitive performance during exposure to office noise or vice versa. Hence, I included urine and saliva samples to measure the possible changes in the excretion of stress hormones.

Individual differences with focus on hearing status

It is evident that different people react in different ways to the same noise (Kjellberg, 1999). The question is whether this reflects a general and stable sensitivity to noise and/or if it may depend on temporary factors (e.g., the situation, mood, health). Boman, Enmarker and Hygge (2005) tested the strength of noise effects on memory as a function of noise source and age, however, they found no interaction between noise and age group and there was no indication of a general interaction between gender and noise. Further, Jones and Davies (1984) found, in their review, no clear relation between noise sensitivity and individual characteristics such as sex and age. Kjellberg (1999) also concluded in his review that there is little support for noise sensitivity to be a specific and stable trait (for a further discussion and definition of noise sensitivity, see for instance the review by Soames Job, 1999). However, when it comes to task performance in noise, there are studies showing that individual differences in working memory capacity (WMC) can play an important role for the magnitude of auditory distraction. People who can exert high cognitive control are also less susceptible to background noise (Sörqvist, 2010). It can, however, be questioned whether this capacity is individually stable over time (or, for instance, is due to motivational factors). According to Kjellberg (1999), another group that is usually highly sensitive to noise is those with a hearing impairment. The focus of this thesis has therefore been directed more specifically to this group.

Hitherto, studies of people with a hearing impairment have mainly focused on how background noise impairs performance and increases listening effort in tasks involving speech processing (Moore, 2003). It is, however, not that common to investigate how this disturbance also applies to non-auditory tasks. Therefore, there is limited knowledge on how hearing impaired persons manage their regular work in open-plan office environments. This is a problem as around 10-15% of the population has some hearing impairment and many of them are in working age. In open-plan offices the employees must be ready to take phone calls and

communicate with colleagues and it might, therefore, not be possible to turn off the hearing aids to reduce the impact of the background noise. The hearing aid helps to amplify the sound to a normal hearing level, but it may also distort the speech signal (Arlinger, 1999), which might lead to more distraction for the hearing impaired.

Individuals with a hearing impairment may be more sensitive to sounds also when they do not use hearing aids due to the recruitment phenomenon. Recruitment refers to the finding that the same increase in signal strength gives a larger increase in perceived loudness in a non-normal ear than in the normal ear (Harris, 1953). Recruitment thus augments the perceived variability of the sound level and may lead to the perception of sharp onsets of sound that could potentially capture attention away from focal task processing much like an auditory deviant (Hughes, Vachon & Jones, 2007).

The focus in this thesis is to test whether the hearing impaired, compared to the normal hearing individuals, are more distracted by noise in a work situation (i.e., non-auditory tasks) with more loud noise.

Type of task and cognitive activity

There are different views of how sound impairs cognitive performance. One theory by Salamé and Baddeley (1982) explains auditory distraction by a phonological interference between the task material and the sound, often referred to as the *phonological loop account*. This account is part of a family of different accounts that collectively can be called *interference-by-content* views. More recent results point, however, towards more support for an *interference-by-process* account (Sörqvist, 2010). Therefore, the interference-by-process account has mainly been the ground for this thesis.

According to the interference-by-process account, the interference of irrelevant sounds with performance is caused by a conflict between similar, competing processes (Marsh, Hughes & Jones, 2008). Generally, involuntary processing of the sound (e.g., interpreting the meaning of speech) produces distraction on tasks that requires the same, but deliberate, processes (e.g., interpreting the meaning of a text). Specifically, involuntary processing of the meaning of speech interferes with deliberate meaning processes (such as interpreting the meaning of text), but not with other types of processes (such as rehearsing the order of sequentially presented to-be-remembered items). Deliberate order processes, in contrast, are vulnerable to disruption from irrelevant order information but not to irrelevant semantic information. When a task involves processing of order information, it is vulnerable to distraction from sounds that changes across time, as the unavoidable processing of the order

of changes in the sound interferes with the processing of serial order in the task (Perham, Marsh & Jones, 2009). This means, consequently, that tasks that do not involve processes that are similar to those involved in processing the sound, can be executed with background sound.

An alternative explanation is *the attentional-resources account* (Cowan, 1995). According to this view, distraction occurs when sounds deviate from a sound stream and directs attention away from the focal task. It is expected by Cowan (1995) that there is a limited pool of attentional resources so when the sound captures attention, less resources are available for the focal task.

A recent view of auditory distraction (i.e., a middle ground between these two latter accounts) has been developed by Hughes, Vachon and Jones (2007), called *the duplex mechanism account*. The assumption is that auditory distraction is either due to the mechanisms of conflicting processes or by attentional capture, as some of the effects can be better explained by one or the other of the theories. It is argued that the first effect (conflict between processes) decays slowly after the noise occurs, while the latter (attentional capture) decays faster. However, there are still a limited amount of studies which support the assumption that these mechanisms should be held apart (Sörqvist, 2010).

It is important to note that the present thesis does not attempt to further investigate and test these basic theories. The theories outlined above merely act as a rationale for how the cognitive tasks, which were used in the studies, were selected and developed.

There are already a variety of tasks that have been developed and tested within the auditory distraction literature. Studies with a basic research agenda have shown that noise impairs, for instance, serial recall (for a review, see Jones & Morris, 1992), word memory (Neely & LeCompte, 1999), and word fluency (Marsh & Jones, 2010). However, the tasks applied within research on open-plan offices often stem from an applied rather than a theoretical ground (for a review of the effects of speech on task performance, see Hongisto, 2005). Some studies have, for example, showed that office noise impairs proofreading (e.g., Smith-Jackson & Klein, 2009; Venetjoki, Kaarlela-Tuomaala, Keskinen, & Hongisto, 2006) and mental arithmetic (e.g., Banbury & Berry, 1998; Schlittmeier, Hellbrück, Thaden & Vorländer, 2008). So far there is, however, only a vague recommendation that open-plan offices are not suitable for difficult/complex tasks and tasks with a high memory load, as these tasks are particularly susceptible to distraction from office noise.

It is apparent, that the next step within this field of research is to focus on the need to make distinctions and specifications of the tasks appearing in open-plan offices, according to

their specific attributes and cognitive requirements. When knowledge is increased on which tasks and cognitive processes that are sensitive to noise, improved recommendations can be given for when open-plan offices are suitable. The difficulty for the researchers is, however, to find tasks that are ecologically relevant, at the same time as the essential cognitive processes, sensitive for office noise, can be distinguished. Table 1 presents a set of dimensions that have been used to characterize the differences between office-related tasks. They illustrate some levels of perspectives possible to take.

In the present thesis, I aimed to develop more specific recommendations for which tasks that can be improved by an open-plan office- or a cell office design, by integrating a macro perspective, with focus on general categories of office-related tasks (e.g., reading, writing, mental arithmetic), and a micro perspective, with focus on more specific processes, or executive functions, that are involved in – or that underlie performance on – those general tasks. The batteries of tasks applied are further described in the method section.

Table 1. Examples of different dimensions that have been used to characterize tasks and to distinguish between different tasks.

Dimension	**Example**	**Source**
Difficulty	easy/complex	Kjellberg & Sköldström, 1991
Fundamental components	remember material/count/read	Banbury & Berry, 1998
Main structure of memory	short term/long term memory	Haka et al., 2009
Stages of memory	encoding/rehearsal/recall/retrieval	Perham & Banbury, 2012
Main processing required	semantic/seriation processing	Marsh et al., 2009
Executive functions	updating/inhibition/shifting	Miyake et al., 2000

Restoration

Most recent empirical and practical work with an explicit concern for restorative environments starts from psycho-evolutionary theory (Ulrich et al., 1991) and/ or attention restoration theory (ART; Kaplan, 1995). The empirical research appears to develop at increasing rate and the research area is expanding into more precisely specifying the mechanisms at work in the restorative processes. It also includes a more diverse sampling of environments and people, includes more sensory capabilities, and deals with the influence of temporal parameters. For more information about the current situation and the related

concerns that have emerged with these diversifications and growth of complexity, see the review article by Hartig and Jahncke (2012).

In this thesis I have focused on two concerns within this field: the effects of sounds on restorative processes and how to tap restoration. First of all it is interesting to note that both of the above mentioned theories have mainly focused on the restorative potential of visual stimuli, which have, so far, made sound stimuli little explored.

Effects of sounds

Numerous studies on restorative environments have shown that nature environments provide a more efficient way for citizens to recover from stress and mental fatigue, than other outdoor urban settings (for an overview see Health Council of the Netherlands, 2004). However, these studies have mainly focused on the visual features promoting restoration in these environments but the reasoning can be applied also to the sound environment.

The sounds that once were abundant and common to perceive, such as rippling water and bird twitter are often masked by other noise sources in cities (e.g., traffic and construction noise). In addition, it is common to be exposed to a variety of noise sources at work, particularly for the modern industry and open-plan office workers, offering no rest from sounds. Hence, if pleasant sounds would become more prominent and workplaces silenced, it may convey positive effects on the inhabitants. Gidlöf-Gunnarsson and Öhrström (2007) have indicated that the combination of pleasant auditory and visual stimuli, (i.e., people having nature close to their residential area) can lead to less irritation towards the surrounding traffic noise, compared to people without close access to nature. Alvarsson, Wiens and Nilsson (2010) have further shown a small indication that nature sounds promote faster recovery from stress, compared to both high/low traffic noise and ambient noise (i.e., ventilation noise) during a break from a stressful task.

Moreover, Jahncke, Eriksson and Naula (2012) have investigated the interaction between auditive and visual stimuli on perceived restoration likelihood and attitudes towards varying environmental resting conditions. The results showed that nature sounds had the highest restoration likelihood, while office noise and broadband noise (e.g., ventilation, traffic noise) got the lowest scores. Further, nature sounds had a higher positive influence on how the nature picture was perceived (i.e., according to perceived restorative qualities, restoration likelihood, attitude, stress, affect) when compared with a picture of an open-plan office. When office noise was present, the difference between the pictures was small (i.e., both pictures were rated low on restorative qualities). These results indicate that the auditive settings appear

to be of significance for restoration likelihood. In Papers I and II of this thesis we test whether different sounds have varying potential to promote actual restoration (i.e., reducing self-reported fatigue and improving performance). How actual restoration of cognitive performance can be measured will be discussed below.

Cognitive measures of attention restoration

To detect the environmental components that promote cognitive restoration, Kaplan and Kaplan (1989) based their Attention restoration theory (ART) on early theories of attention. They referred to James (1892), who dichotomized attention into two components: involuntary attention (when attention is captured by something inadvertent) and voluntary attention (when cognitive control processes are used to direct attention). Later on Kaplan and Kaplan (1989) have specified inhibition as the key component for sustained attention and the mechanism in need of restoration. A mixture of performance measures have been applied within this field, not necessarily tapping inhibition.

For this thesis I took help from working memory research to further define the inhibition mechanism and the tasks developed to tap this mechanism. The theoretical basis comes mainly from a study by Friedman and Miyake (2004). Their results showed that there are at least two inhibitory mechanisms that should be distinguished. First, a mechanism is involved in inhibition of motor responses or distracting stimuli. This mechanism (*response inhibition*) is tapped by tasks such as the Stroop task, the Flanker task and the Sustained attention to response test (SART). Common for these tasks is the requirement to inhibit a response to a flanker or predefined target. Second, a mechanism is involved in inhibition (or suppression) of no-longer relevant information activated in working memory. This mechanism (*cognitive inhibition*) is tapped by tasks that involve proactive interference. For example, in a short-term memory task participants are presented with sequences of lists consisting of 5-10 words drawn from the same category (i.e., animals). After each list, the participants are required to recall the words from the most recent list in free order and ignore words from earlier lists. The key assumption is that to avoid recall of post lists, the words from those previous lists have to be deliberately inhibited (or suppressed) so as to not intrude into the recall process. There is also neuroimaging support for dividing the central executive into several relatively independent functions. These control processes have shown to be resource limited and that they can become temporarily depleted (Persson, Welsh, Jonides, Reuter-Lorenz, 2007).

This distinction has, however, not been made earlier within the research field of restorative environments. The cognitive measures applied within this field of research are listed and shortly described in Table 2, according to year of publication. The tasks are further grouped according to the hypothetical main mechanism involved. Important to note is that only two of the studies listed (i.e., Hartig et al., 1991; Hartig et al., 2003) showed improved performance after a visit in a restorative environment, when excluding the studies in which fatigue was not established with a measure prior to the treatment. Accordingly, few studies have tapped fatigue and there is, therefore, yet minor support for the ART-theory with regard to actual restoration of attention. There might be several reasons for these inconsistent results, for instance, a lack of any substantial need of restoration at the time the participants are exposed to the (presumably) restorative environment, too short exposure for restoration to kick in, or the use of measures that are insensitive to the assumed mechanism that has, in fact, been restored. The general pattern is that most studies have tested response inhibition (see Table 2), except those using the Necker cube pattern control task (NCPT), which is supposed to tap inhibition of a reversal in perceptual pattern, or satiation. Interestingly, some recent studies (see the end of Table 2) do not focus on inhibition, instead the tasks used have involved working memory (WM) processes. To the best of my knowledge, no study has so far tested cognitive inhibition as described by Friedman and Miyake (2004). Therefore, the focus in Paper I of this thesis was to include measures of the two different inhibition mechanisms (i.e., cognitive and response inhibition), to test if these processes get fatigued with prolonged work during noise, and subsequently restored after a break. According to Table 2 there seem to be a progress towards task which involves different processes of WM. This development can also be fruitful for the field, as it opens up for the possibility that other cognitive processes within WM can become depleted. Therefore, in Paper II the cognitive inhibition task is replaced with an arithmetic task which has shown to be fatiguing to perform in formal noise studies.

Table 2. The cognitive measures of attention restoration applied within the research field on restorative environments.

Test Name	Description	Mechanism(s)	Example
Proof reading	Find errors in a text.	Visual search and stimulus inhibition	Hartig et al. (1991)
Search and memory test (SMT)	Search for specific target letters in the line of letters presented.	Visual search and stimulus inhibition	Hartig et al. (1996)
Necker cube pattern control task (NCPCT)	Hold attention to one three-dimensional cube pattern so it does not reverse pattern.	Pattern inhibition or satiation	Hartig et al. (2003)
Posner's attention orienting task (PAOT)	Respond in different ways to targets.	Response and stimulus inhibition	Laumann et al. (2003)
Symbol digits modalities test (SDMT)	Identify symbol-digit substitutions.	Visual search and stimulus inhibition	Bodin & Hartig (2003)
Finding A´s test	Detect words containing the letter "a".	Visual search and stimulus inhibition	Lethbridge et al. (2005)
Sustained attention to response test (SART)	Press a button when a number is presented, except when a target number is presented.	Response inhibition	Berto (2005)
Attention network test (ANT)	Suppress flanking arrows and respond to the direction of a target arrow.	Response and stimulus inhibition	Berman et al. (2008)
Reading span	Remember the last word in each sentence.	Working memory	Raanaas et al. (2011)
Digit span	Repeat a sequence of numbers in the same or reversed order.	Working memory	Berman et al. (2012)

Research issues

Paper I

The research issues of Paper I were:

- Is there a stronger negative effect of a high office sound level (51 dB LAeq), compared to a low level (39 dB LAeq) on basic working memory processes, self-ratings (motivation and fatigue) and physiological measures of stress (saliva and urine samples)?
- Are there effects of experimentally manipulated sound conditions in an interpolated break period of seven minutes on subsequent cognitive work performance, self-ratings of mood and fatigue, and saliva cortisol levels?

Paper II

The research issues were basically the same as in Paper I, with the addition/change of:

- Is there an interaction between hearing characteristics and performance/fatigue/stress when exposed to a high office sound level (60 dB LAeq), compared to a low level (30 dB LAeq)?
- Do effects of varying sound conditions emerge on restoration (one of the performance measures was replaced), when the interpolated break period is prolonged to 14 minutes?

Paper III

The choices of research issues in Paper III were directed at testing a model developed by Hongisto (2005), which predicts the decrease of cognitive performance as a function of speech intelligibility. The research issues were:

- How much is cognitive performance during irrelevant background speech affected by varying degrees of speech intelligibility?
- Are some cognitive tasks more affected than others?

Paper IV

The research issues of Paper IV were:

- Is performance in tasks based on semantic processing (e.g., word memory, semantic fluency and information search) more impaired by irrelevant background speech than tasks based on other or less semantic cognitive processes (e.g., counting and phonemic fluency)?
- Does a change in type of processing demands modulate the task's sensitivity to disruption from irrelevant speech?

General method

Research settings

Papers I, II and III were performed in a simulated open-plan office setting at the University of Gävle. For Paper III the open-plan office was rebuilt in a new laboratory building (see Figures 1a and b). In the simulated open-plan office we kept the different environmental variables constant (e.g., ventilation, temperature and illumination). Paper IV was performed in sound proof rooms where the participants worked alone in the room.

In Paper I and II the participants were exposed to re-played office-noise through loudspeakers at the walls and in Paper III and IV the participants were exposed to speech through headphones. During the break period (i.e., Paper I and II) the different sounds were played back by headphones and during this time no other noise was played back in the room.

Figures 1a and *b*. The simulated open-plan office from Paper III.

Independent variables

The independent variables in the four papers are shown in Table 3. In the first two papers the mean level from all kinds of sound sources at an office, such as speech, phones and people walking were in focus. In Paper II we investigated whether the sound level effects were more pronounced for individuals with a hearing impairment. In the last two papers background speech was in focus. In common for all studies was the successive testing of different cognitive tasks.

In Paper I and Paper II the work sessions in noise were followed by a break with different contents (involving different visual and sound stimuli) for the participants.

Each manipulation is described in more detail in the summarized method section for each paper.

Dependent variables

Different dependent measures have been employed in the four papers (see Table 4) and each measure is described in detail within each paper.

As it was not obvious which tasks to start with, that would be sensitive for sound level changes, a combined battery of measures were applied in Paper I, including measures of executive functions (updating, shifting and inhibition), semantic- (word memory, reading comprehension) and order processing (serial recall), working memory capacity (i.e., operation- and reading span), and fundamental components of office work (logical problems).

In Paper II the tasks which showed not to be sensitive for sound level changes from Paper I were excluded (e.g., measures of some of the executive functions), tasks showing roof effects were changed to become more difficult (e.g., reading comprehension), and two new tasks were developed to test fundamental components of office work (e.g., information search and math). One task was also kept the same (i.e., serial recall) to open up for comparisons between Paper I and Paper II.

In Paper III the focus was on fundamental components of office work (i.e., to remember material, to search for relevant information, to count, and to generate words), though the tasks can still be distinguished by the different memory structures, stages of memory and main processes required by the task.

In Paper IV some of the tasks were the same as in Paper III. However, the focus was on testing tasks requiring high degrees of semantic processing (e.g., word memory, semantic fluency and information search) compared to tasks based on other or less semantic cognitive processes (e.g., counting and phonemic fluency). A new task (word memory: category- and structural word finding) was also developed to change the requirements of semantic processing by varying the processing instruction (i.e., changing the mental operations that participants perform on the to-be-remembered material), without changing the test material per se.

Table 3. The independent variables in the four papers

Independent variables	Paper I	Paper II	Paper III	Paper IV
Sound level (irrelevant sounds)	x	x		
Restoration period	x	x		
Hearing status		x		
Levels of irrelevant speech intelligibility			x	
Presence/no presence of irrelevant speech				x
Types of tasks and cognitive activities	x	x	x	x

Table 4. The dependent measures in the four papers are shown in Table XX.

Cognitive measures	Paper I	Paper II	Paper III	Paper IV
Updating	x			
Shifting	x			
Response inhibition (Flanker task)	x			
Logical problems	x			
Operation span	x			
Reading span	x			
Reading comprehension*	x	x		
Serial recall	x	x		
Response inhibition (SART)	x	x		
Word memory (Proactive interference)	x	x	x	
Arithmetics		x		
Math		x	x	x
Information search task (Search task)		x	x	x
Word fluency (Word generation)			x	x
Memory: category- and structural word finding				x
Self-reports				
SOFI (fatigue and motivation)	x	x		
Stress hormones				
Cortisol (saliva samples)	x	x		
Catecholamines(urine samples)	x	x		

Paper I:

Open-plan office noise: cognitive performance and restoration

Method

The study included 47 students from the University of Gävle, 27 female and 20 men with a mean age of 26 years. All participants reported their hearing and vision to be normal. The research was carried out in a laboratory simulating an open-plan office on Tuesdays and Thursdays between 2.00 and 5.00 pm. The participants went through one practice session and two experimental sessions, one each with a low (39 dB LAeq) - and a high (51 dB LAeq) noise condition. In each experimental session they started with a relaxation period of 15 minutes and then worked for two hours with tasks involving basic working memory processes (Updating, Shifting, Word memory (cognitive inhibition), Response inhibition, Flanker task, Logical problems, Operation- and reading span, Reading comprehension, Serial recall).

In *the Shifting task* the participants were required to switch between two different categorization operations. The task consisted of number-letter pairs (e.g., 3E) presented in a clockwise rotation around all four quadrants on the computer screen. When the number-letter pair was presented in the top two quadrants, the participants were to indicate whether the number was even or odd, and when presented in the bottom two quadrants, they were to indicate whether the letter was a vowel or a consonant. The participants responded by pressing different keys for even/odd and vowel/consonant answers. *The Updating task* consisted of seven lists of 10 two-digit numbers. For each list the participants were instructed to recall the three smallest numbers in the order of presentation. This task measures the ability to update information in working memory, as the smallest numbers continuously need to be updated. In *the Word memory task* the participants were asked to learn words from ten lists with five words each. The lists were composed of words drawn from the same category. After being presented with a given list of five words, the participants were required to recall the words from the most recent list in free order and ignore (suppress) words from earlier lists. This task is supposed to tap proactive interference (i.e., the ability to inhibit information that once was relevant for recall but has since become irrelevant for the task). In *the response inhibition task* (i.e., Sustained attention to response test, SART) digits from one to nine were presented repetitively and the participants were told to respond with a key press to all numbers except number three. *The Flanker task* is another measure of response inhibition. The participants viewed strings of five letters composed of H and S (e.g., HHHHH, HHSHH). They were told to respond to the central letter by pressing “h” or “s” on the keyboard,

inhibiting the other letters (flankers). In *the Logical problems task* the participants were presented with logical problems and were told to answer whether the conclusion was true or false (e.g., All A are B. Some B is C. Conclusion: some A is C. Is this conclusion true?). In *the operation span task* the participants were presented with sets consisting of a mathematical operation and a word (e.g., Is (4/2) + 1 = 3? and then the word "Rose"). The participants were told to answer whether the mathematical expression was true or not. They were further told to remember the word presented after each mathematical operation. After three to seven tasks the participants were asked to recall all the words presented. This task requires the immediate suppression of the mathematical operations and suppression of words from earlier lists. *The reading span task* was similar to the previous task. The participants were to decide if a sentence was normal or abnormal and then remember a two-digit number (e.g., "The cloud laugh yellow", Is the sentence normal? and then the number 32). After three to seven tasks the participants were to recall all the recent numbers presented. In *the Reading comprehension task* the participants were presented to ten short texts. After each text the participants were required to answer one question with four alternative answers (only one was correct). Half of the questions were about the meaning of the text and half of the questions were about a missing word in the text. *The Serial recall task* had two versions. In one version of this task, the participants were told to remember a string of seven one digit numbers and then recall them in the correct order. In the other version of this task, they were told to remember a string of seven letters and recall them in the correct order.

After each work session in noise the participants went through a break of seven minutes in one of the four break conditions (river movie with sounds, only river sound, silence, office noise). *Pretest* and *Postrest* we took urine samples (catecholamines), and five times during the session we took saliva samples (cortisol) to measure the stress levels. The participants also gave reports on motivation and fatigue *Pretest, Postwork* and *Postrest*. The whole procedure took about three hours to complete, and seven to eight participants were tested at each occasion.

Results and discussion

At the outset we intended a within-person design for the noise manipulation. However, the analysis revealed that performance in the low noise condition was better when this condition was presented first to the participants. To safeguard against these order effects we therefore employed a between-person design by analyzing the performance in the first session only. For the other measures (psychophysiological stress and self-ratings of fatigue) we had no

interaction between noise and session order. Hence, noise is treated as within-subjects factor as planned for these measures.

The analysis showed that the participants remembered fewer words and had more missing answers during high noise compared to low noise. However, there were no further significant effects of sound level on the other cognitive measures. Some of the measures might have been independent of the sound level manipulation, as performance might only be impaired when also the intelligibility of the background speech is changed. The participants might also be able to compensate for aversive sounds by exerting extra effort during this short two hour exposure time. As expected the participants felt more tired and less motivated after they had worked for two hours in high noise compared to low noise. This is in line with other studies indicating fatigue and motivational deficits among groups exposed to noise (reviewed by Kjellberg, 1997). In opposition to what we expected, no effect of sound level was shown on psychophysiological stress. There was just a significant decline in cortisol- and norepinephrine levels over time. This possibly reflects the circadian rhythm with less secretion in the afternoon.

The analysis regarding the break showed that the participants who saw a movie of a flowing river with matching sound reported having more energy compared to the participants who just listened to river sounds, or those who continued to listen to office noise. Remaining in office noise during the break also affected motivation more negatively than listening to river sounds or watching the nature movie. There were, however, no significant effects of the break condition on the cognitive or physiological measures. This might be due to the small sample for comparison in each break condition and/or the brief period allowed for restoration.

Paper II:

Performance, fatigue and stress in open-plan offices: the effects of noise and restoration on hearing impaired and normal hearing individuals.

Method

The study included 20 hearing impaired (9 female and 11 men, median age = 53) and 18 normal hearing persons (8 female and 10 men, median age = 48). The participants came from different working areas and had different education levels. The participants with hearing impairment were recruited from the Swedish association of hard of hearing people and those who reported having severe tinnitus and/or Meniéres disease were excluded. We also recruited matched normal hearing participants following the criteria of the same gender, age

(acceptable with some years of difference), occupation and education as the hearing impaired persons. All participants hearing ability were screened. The criterion to be included in the hearing impaired group was a mean hearing loss of 28 dB or more over the frequencies 500, 1000, 2000 and 4000 Hz, which did not give any overlap between the two groups. The research was carried out in a laboratory simulating an open-plan office on Tuesdays and Thursdays between 4.00 and 7.00 pm. The participants went through one practice session and two experimental sessions, one each with a low (30 dB LAeq) - and a high (60 dB LAeq) noise condition. In each experimental session they worked for two hours with tasks involving basic working memory processes (Word memory, Response inhibition, Arithmetic, Math, Search task, Reading comprehension, and Serial recall).

The Word memory task is supposed to tap proactive interference (i.e., the ability to inhibit information that once was relevant for recall but has since become irrelevant for the task). In this task the participants were asked to learn words from eight lists with ten words each. The lists were composed of words drawn from the same category. After being presented with a given list of ten words, the participants were required to recall the words from the most recent list in free order and ignore (suppress) words from earlier lists. In *the response inhibition task* (i.e., Sustained attention to response test, SART) digits from one to nine were presented repetitively and the participants were told to respond with a key press to all numbers except three target numbers (i.e., 2, 5 and 9). *The Arithmetic task* was a computational task with ten single-digit numbers, which were presented one by one on the screen. The operation to perform (+ or -) was presented between the numbers. The participants controlled the presentation speed. When all the ten numbers were presented the participants typed in the answer. In *the Math task* participants were required to add double-digit (e.g., easy task: 44+38) and triple-digit numbers (e.g., difficult task: 122+435). Each experimental block consisted of 30 expressions. In *the Search task* the participants were asked to find an object that met a set of criteria by searching through a table with information. The tables contained twenty rows and seven columns. For each row, an object was presented (e.g., a house), and each column described one aspect of the object (price, location, building year, etc.). The participants were asked to find the object that met a set of criteria (e.g., "Which building of row house type was built after the 70-s and is the most expensive?"). *The Reading Comprehension task* consisted of texts taken from the Swedish National University Aptitude Test. One sentence at a time was presented and the participant decided when the next sentence should be presented by clicking the space button. In 25 of the 43 sentences one word was missing and the participants were required to choose between four alternatives. When all the

text was read, two variations of memory questions were posed. In the first set the participant was presented with a sentence and was asked to judge whether the sentence was taken from the text read or not. In the second set there were questions about the information stated explicitly in the text, (e.g., years, book titles, places, names). In *the Serial recall* task the participants were told to remember a string of eight one digit numbers (i.e., 1-8) and then recall them in the correct order.

After the work session in high noise the participants went through a break of 14 minutes in one of two break conditions (nature movie, office noise). After the work session in low noise all participants went through a break of 14 minutes in quiet. To measure the stress levels we took three urine samples (catecholamines) at *Prework, Midtime* and *Postrest*, and four saliva samples (cortisol) during the session. The participants also gave reports on motivation and fatigue *Prework*, *Postwork* and *Postrest*. The whole procedure took about three hours to complete, and one to eight participants were tested at each occasion.

Results and discussion

Originally, we intended to employ a design with noise conditions as a within-subjects variable, but the analysis again showed an interaction between performance and session order for the cognitive measures. To safeguard against these order effects we altered to a between-person design, analyzing performance in high and low noise from the participants´ first session only.

The analysis showed that the hearing impaired participants were more affected by high noise than the normal hearing participants, with decreased performance in semantic tasks involving memory. The hearing impaired remembered less from the content of the text they had read, and tended to recall fewer words in the word-memory task during high noise than in low noise. Conversely, the normal hearing participants contradicted the expectations by performing better in the high than in the low noise condition in both the math- and reading task, and tended do so in the word memory task. The analysis also showed that the participants became more uninterested (less motivated) over time in low noise, than in high noise, suggesting that more noise might function as stimuli when tasks, that can be experienced as boring, must be performed.

During high noise the hearing impaired participants were as expected more tired in comparison with the normal hearing participants. There was also a small tendency that the hearing impaired participants had higher stress hormone levels (saliva cortisol) during high noise than in low noise. However, the only significant effect that emerged was the decrease of

stress hormones over time. This is consistent with the decline that occurs as a part of normal circadian variation.

Regarding the break period the analysis showed different patterns according to hearing status. The normal hearing participants showed improved arithmetic performance and motivation after a nature movie and decreased performance and motivation after continued noise exposure. For the hearing impaired participants, continued noise during the break increased motivation and performance, while the movie did not. No support for a difference between the break conditions was found in the stress hormones.

The results of this paper (Paper II) are in many ways comparable to Paper I. However, there are some discrepancies in the results, which may or may not be due to differences in, for instance, the cognitive tests employed, the sounds employed, and/or the characteristics of the participants. For instance the participants in Paper I were young (mean age = 26 years) students, while the participants in Paper II were older (mean age close to 50 years) and had less of formal schooling. To probe whether this difference had any impact on the difference in results between the two papers, a follow up statistical comparison was made between the results on comparable tests from participants in Paper I and Paper II. This comparison showed a significant difference in serial recall performance (a measure included in both studies) between the normal hearing participants in the two studies during low noise, $t\,(53) = 2.27$, $p < 0.05$. The normal hearing students in Paper I with students, performed better than the older normal hearing participants in Paper II. This performance difference between the normal hearing groups in these two studies may be an important explanation of why the results of Paper II differ somewhat from the results of Paper I.

Paper III:

Cognitive performance during irrelevant speech: effects of speech intelligibility and office-task characteristics.

Method

The study included 47 students recruited from the University of Gävle. All participants reported their hearing and vision to be normal. Five of the participants were excluded before analysis because one of the persons in one of the groups disrupted the others, leaving 42 for the statistical analyses (18 female and 24 men, mean age = 24). We tested a model developed by Hongisto (2005), which predicts the decrease of cognitive performance as a function of speech intelligibility (Figure 2, curve A). We used the *Speech Transmission Index***,** STI (IEC

60218-16) to determine the conditions of speech intelligibility. The Speech Transmission Index is an objective way to depict how well speech is perceived in a certain room acoustic condition and takes into account the degradation effect of reverberation and masking noise. The closer the value is to 0, the more information is lost and at the value of 1 the speech is perfectly intelligible. The STI-values of the acoustic conditions tested in this study were 0.00, 0.08, 0.16, 0.23, 0.34 and 0.71. STI 0.00 represented silence (i.e., without speech) during which masking sound was played at a level of 33 dBA. The other five conditions contained speech of increasing intelligibility and masking sounds, while maintaining a constant total sound level of 51 dBA. The masking sound was anechoic and monaural filtered pink noise (Adobe 3.0). The experiment was carried out in a laboratory simulating an open-plan office. The session started with computerized background questions, followed by a practice period of all tasks (Word memory, Information search task, Math, Word generation (Semantic- and Phonemic fluency) for five minutes in quiet.

In *the Word memory task* participants memorized eight lists of words. The lists comprised ten words each, drawn from the same category. After being presented with a given list of ten words, the participants were required to recall the words from the most recent list in free order. This task puts substantial demands on both encoding and retrieval processes in semantic short-term memory. *The Information search task* taps processes required to search through and understand the contents of a table of information, while successively updating and memorizing information that accords with a target criterion. The tables contained twenty rows and seven columns. For each row, an object was presented (e.g., a house), and each column described one aspect of the object (price, location, building year, etc.). The participants were asked to find the object that met a set of criteria (e.g., "Which building of row house type was built after the 70-s and is the most expensive?"). *The math task* was an addition task of triple-digit numbers, which requires some kind of episodic or working memory (i.e., storage of a solution). In *the Word generation: semantic- and phonemic fluency tasks* the participants were given 60 seconds to generate (write) as many exemplars from a given category as possible. Both tasks make similar demands on retrieval from long term memory but rely on different activation and search processes. After the practise of the tasks each participant executed the five tasks in all acoustic conditions. The tasks and the acoustic conditions were presented in randomized order for each participant. After half of the time the participants had a 15 minutes break in another room. The whole procedure took about 3h 15 minutes and seven to eight participants were tested at the same time.

Results and discussion

The analysis showed a main effect of acoustic condition on task performance, in accordance with Hongisto´s (2005) model in two tasks (word memory and math) out of five. In another task (information search task) we also found a difference in performance between the highest and lowest STI condition. The average of these three tasks is presented in Figure 2 (curve B). The figure shows that the participants' cognitive performance decreased as a function of acoustic conditions (i.e., the higher STI-value/intelligibility, the worse performance). This general function followed a significant linear and cubic trend, which indicates a linear reduction in performance with a knee both around STI 0.16 and a knee from STI 0.34, where the curve flattened out. This general form of the STI - performance functions deviated somewhat from Hongisto´s model (Figure 2, curve A). The steepest slope of overall performance decrease was located between STI 0.23 and 0.34, and the difference between 0.34 and 0.71 was negligible. Hongisto suggests, however, that the steep slope of performance deterioration flattens out later, just above STI 0.50. Also, the type of function was different depending on which task was performed, which was not considered in Hongisto's model. The math task which consists of simple addition was not as vulnerable to varying levels of speech intelligibility as the Word memory task, based on semantic short-term memory. In the Word memory task performance decreased with about 5 percent from baseline (STI 0.00) to the most critical STI-value for performance (i.e., STI 0.34) and in the Math task there was less than a 3 percent decrease. The two word fluency tasks were not at all affected by speech. One explanation may be that they are based on long-term memory retrieval and do not need encoding or rehearsal of a to-be remembered material, which can make tasks less vulnerable to distractions from background speech (Naveh-Benjamin, Craik, Perretta & Tonev, 2000).

The results of this study are useful in determining an appropriate target level for sound in offices and designates that the aim should be a STI-level less than 0.50 (between the speaker and the listener) to influence performance. However, how positive the reduction in speech intelligibility will become depends on the task type (i.e., the cognitive processes that underpin the task).

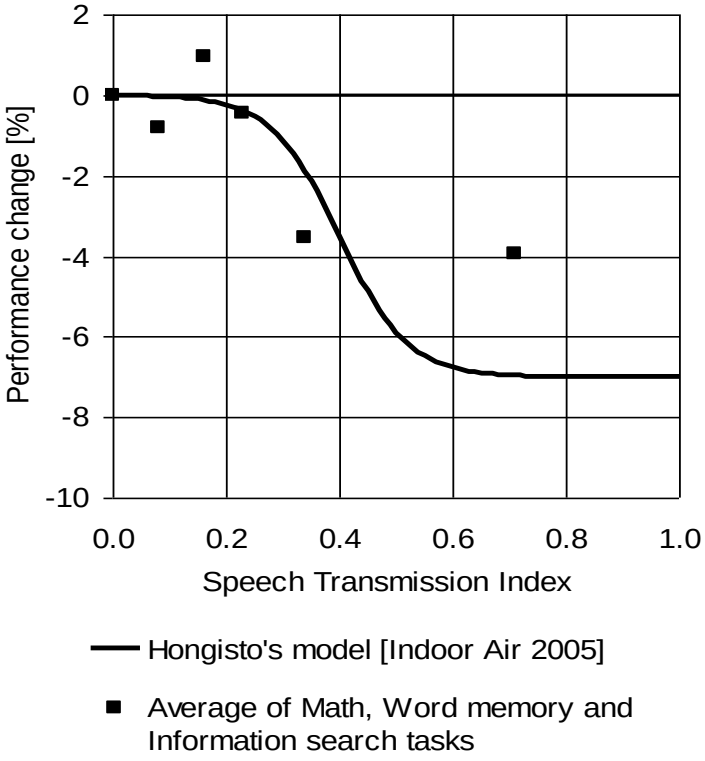


Figure 2. The schematic prediction model which gives the change of performance as a function of the Speech Transmission Index (STI). The model shows that the magnitude of successful task performance will start decreasing when STI exceeds 0.2 and the largest decline will be reached above 0.50 (0.00 = not intelligible; 1.00 = perfectly intelligibly speech). The present results indicate that the steepest slope of overall performance decrease was located earlier, between 0.23 and 0.34 and that the difference between 0.34 and 0.71 was negligible.

Paper IV:

Open-plan office noise: the susceptibility and suitability of different cognitive tasks for work in the presence of irrelevant speech.

Method

The participants were 24 students recruited from the University of Gävle (8 female and 16 men, mean age = 25). All participants reported their hearing and vision to be normal. The experiment was carried out in sound proof rooms at the University of Gävle.

A within-person design was used with two noise conditions (quiet versus irrelevant background speech) and four different tasks expected to involve diverse cognitive processes (Information search task, Math task, Word generation: semantic- and phonemic fluency, Memory: category- and structural word finding).

The two noise conditions were presented via headphones. The quiet condition (i.e., including the normal background noise in the room) was approximately 30 dB (A) and the irrelevant speech was played back at an average level of 51 dB (A). The speech material was the same as in Paper III. The sentences and the tasks were presented in random order by the computerized program during the experimental session.

In *the Information search task* the participants were asked to find an object that met a set of criteria by searching through a table with information. This task is based on episodic memory, with rehearsal and updating of the to-be-remembered material. *The math task* was an addition task of triple-digit numbers, which requires some kind of episodic or working memory (i.e., storage of a solution). In *the Word generation: semantic- and phonemic fluency tasks* the participants were given 60 seconds to generate (write) as many exemplars from a given category as possible. The tasks requires retrieval from long-term memory, with either a semantic or phonemic activation of words, and do not involve rehearsal of a to-be-remembered material. In *the Memory: category- and structural word finding tasks* the participants were instructed to remember all words within a named category, or words beginning with a certain letter, while searching lists of words. These tasks were based on either semantic or structural analysis of the targets, however, both tasks put high demands on episodic memory and presumably rehearsal of the to-be-remembered material.

Results and discussion

The analysis revealed a main effect of background speech on memory from structural word finding, on memory from category word finding, and information search. More precise, performance decreased from quiet to background speech with 10.6 percent for memory from structural word finding, 6.5 percent for memory from category word finding, and 8.7 percent for the information search. As expected there was no effect of background speech on math performance or on phonemic fluency, but, unexpectedly neither was there an effect of background speech on semantic fluency. The results of this study showed that the tasks which require episodic memory and the process of rehearsal — such as word memory and information searching — appears to be better performed during quiet. Word fluency (based on material stored in long-term-memory) and simple counting, however, were less susceptible to

disruption via the presence of irrelevant speech. The conclusion is that it is important to consider which work environments are optimal for each kind of task component as work tasks differ in how vulnerable they are for background speech.

General discussion

Open-plan office noise and some practical implications

The current work showed that open-plan office noise may have a negative impact on fatigue, motivation and performance, especially when tasks are performed which are based on memory and rehearsal of information.

First, we investigated the effects of different sound levels (i.e., of all kinds of sound sources, such as speech, phones, people walking), and then the focus was shifted more directly towards background speech, the most disturbing noise source in open-plan offices (Kaarlela-Tuomaala et al., 2009). Paper I included a reduction of the sound level by 12 dB, and Paper II by 30 dB. Important to note is that no extreme values were used when we found negative effects of the high noise conditions. The high noise conditions consisted of levels around 50-60 dBA, which are common equivalent values for open-plan offices (Venetjoki et al., 2006). It can, however, be hard to reach 30 dB reductions in open-plan office designs without putting up walls.

The common way to reduce the overall sound level is to put in absorbents. However, too many absorbents in an open-plan office may reduce the natural masking of background speech, when the overall murmur is reduced. As shown in Paper III, the more intelligible the speech sounds are, the more is performance impaired. The research ground for Paper III was Hongisto´s model (2005) which shows that performance will start decreasing when STI exceeds 0.2, and that the largest decline will be reached above 0.50. However, the results of Paper III indicated that this model needs to be revised as the steepest slope of overall performance decrease was located earlier, at STI 0.34. Further, the change between STI 0.34 and 0.71 was negligible, which give further strength to the assumption that the largest decline in performance is already reached when speech just begins to get intelligible. A maximum performance decrement above STI 0.50 (as proposed by Hongisto) was observed only with one task (i.e., the information search task), while two tasks (i.e., semantic- and phonemic fluency tasks) were not at all affected by speech.

There are already some studies which supports the notion that it is possible to design an open-plan office so that STI below 0.5 is achieved in a nearby workstation (2.5 m), or at least

in a workstation 5 m away (Keränen et al., 2011; Virjonen et al., 2007; Virjonen et al., 2009). The speech masking levels used in Paper III shall, however, not be used as guidelines for designing open-plan offices. Quite high masking sound levels (up to 51 dBA) were used to create the lowest STI-values. The masking levels suggested are usually between 40 and 45 dBA. Care must also be taken when considering masking sounds, as the results dealing with masking are few and unclear. So far, some studies have shown that masking can help decrease disturbance of speech and increase performance (e.g., Lowen & Suedfelt, 1992; Hongisto, 2008; Helenius & Hongisto, 2004). However, Keighley and Parkin (1979) have tested twelve different masking conditions in a real open-plan office and they found contradictory results. None of the conditions were perceived as effective or giving an overall improvement, compared to when no masking was introduced. The disadvantage with providing masking is that at some point the increased noise levels will lead to increased annoyance as well as to increased speech levels, which can lead to a vicious circle (Veitch, Bradley, Legault, Norcross & Svec, 2002). Moreover, the masking noise should follow the frequency of speech for efficient masking. Jiang, Liebl, Leistner and Yang (2012) have therefore tried masking produced by time-reversal of the target speech (i.e., the target speech was divided up into short segments that were then reversed and pieced back together as a masker). However, they found no support for increased performance in a short term memory task (i.e., serial recall) with time-reversed maskers. Further, perceived annoyance was the same, or worse, compared to the normal noise masker. Another consequence of masking may be stress related symptoms, which has shown to be the matter for noise-sensitive individuals (Persson-Waye et al., 2002). In sum, the inconsistent results so far cannot clearly tell if it is a good idea to invest in additional masking noise, as it has been difficult to find a masking that is both effective and acceptable. However, a combination of absorbents and high screens can help reduce the sound levels to a certain degree, though, it can be difficult to reach the lowest STI-levels.

It can be argued that the negative effects of open-plan office noise are related to people characteristics and that the solution is to find people who fit to the open-plan solution. Another way of dealing with this issue is, however, to try to find a work solution that fit to the employees and the tasks they perform. Paper I showed that a change in sound level (i.e., but not intelligibility) affected word memory performance. Earlier it has been shown that a change in sound level of irrelevant speech does not affect performance (Ellermeier & Hellbrück, 1998). However, the present results indicate that even a small change in sound level may lower performance in memory based tasks, when all sound sources are reflected (i.e., when more than just the speech sounds are in focus). Further, Paper IV showed that

when speech is perfectly intelligible it affects tasks which require episodic memory and the process of rehearsal — such as word memory and information searching. However, Word fluency, which is based on activating material stored in long-term-memory, was not susceptible to irrelevant speech. This supports earlier findings showing that division of attention at encoding (i.e., attentional capture of a sound) reduces memory performance markedly, while division of attention at retrieval has almost no effect on memory performance (Naveh-Benjamin, Craik, Perretta & Tonev, 2000). Moreover, Paper III showed that even though speech intelligibility was lowered to STI-levels of 0.34, word memory and arithmetics remained vulnerable to the speech sounds.

When going back to Table 1 (Introduction section - *Type of task and cognitive activity*) and the different dimensions that have been used to distinguish between different tasks, the present results indicates that tasks distinguished by their difficulty (i.e., more complex tasks than easy tasks), fundamental components (i.e., count, search and remember material, but not comprehend texts or generate words), main structure of memory (i.e., short-term memory but not long-term memory) and stages of memory (i.e., rehearsal of material but not retrieval) were the most sensitive to open-plan office noise. However, the results of the present thesis do not indicate any clear effects of open-plan office noise on tasks distinguished by their level of semantic demands (Paper IV), or executive function required (Paper I). It might be that this micro perspective with focus on specific processes is better tested with another experimental design, with more control and not so many variables involved. More research is therefore needed to address these concerns. To sum up, the present results indicate that open-plan office designs are not suitable for employees who need to perform tasks which are based on episodic memory and repetition of information for later recall. For example, when writing client replies where a frequent search and uphold of new information in memory is required.

It is not just the types of noise, layout of the office or the kind of task performed that can affect the employees. Special consideration needs to be addressed also to the individual prerequisites, such as hearing status investigated in Paper II. The results showed that the hearing impaired were more distracted and fatigued by a higher sound level than normal hearing individuals. For example, the hearing impaired remembered less from a text they had read, and tended to recall fewer words in a word-memory task during high noise than in low noise. Conversely, the normal hearing participants performed better in the high than in the low noise condition in both the math- and reading task. One explanation might be that more noise can function as stimuli when tasks, which can be experienced as boring, must be performed. Possibly, noise at 60 LAeq was more distracting for the hearing impaired as they

presumably are more sensitive for noise when the sound signal is distorted. In summary, the results of Paper II indicates that other office solutions might be needed for the hearing impaired (e.g., quiet rooms) to enhance performance and wellbeing for these individuals.

Unexpectedly, neither Paper I nor Paper II showed any effect of sound level on psychophysiological stress. There was just a significant decline in cortisol- and norepinephrine levels over time. This possibly reflects the circadian rhythm with less secretion in the afternoon, and/or that the tasks employed were perceived as quite easy to the participants, which can make them less stressful to perform in noise. However, there are also field studies which results emphasize the importance of examining the effects of noise over longer exposure times. For example, Evans, Bullinger and Hygge (1998) found that chronic exposure to noise (i.e. aircraft noise) over a two year period elevated higher physiological stress responses, compared to a control group. Therefore effects of office noise might only be apparent for employees who have worked in open-plan offices for several weeks.

In sum, the results of this thesis showed that both actions for reducing the overall sound level and the intelligibility of background speech can improve performance and decrease feelings of fatigue. Some of the actions towards accomplishing this are listed below:

- Attenuate noise at its source (e.g., pads on chairs, vibrating quiet phones)
- Decrease the propagation of the noise (e.g., isolate printers in a separate room)
- Absorption (e.g., ceiling panels, wall panels, screens, curtains, carpets)
- Apply masking noise with care (e.g., in the room or individually by each desk)
- Individual noise reduction (e.g., use earplugs)
- Placement of employees (e.g., isolated groups, sit close to those you work most with)
- Ethical rules (e.g., speak quiet, not over others head)
- Quiet rooms (for phone calls, meetings, concentration/demanding work)
- Cell offices (for employees with individual characteristics and tasks not suitable for noisy backgrounds, and for people who are noisy or who cannot stand background noise)

The burden of noise in open-plan offices

If the main reason behind the decisions of moving to an open-plan office is the possibility to save money, it is interesting to have a look also at the cost that can be expected for reduced performance due to a poorer acoustic environment. Consider an example from a typical open-

plan office with 110 employees, working 40 hours/week (43 working weeks/year), having a mean salary of 25 500 Swedish crowns, plus the addition of 52 per cent for social security contributions. Judging from the results of Paper III and IV performance decreased with irrelevant background speech, compared to quiet, with between 2 - 10 percent depending on which task was performed. A conservative estimate with a performance reduction of only 2 percent (loss of working hours * salary/hour * social security contribution) gives a total loss of around 1 000 000 Swedish crowns/year (around 120 000 Euro/year) for 110 office employees. On top of this are costs for increased risk for illness and sick leaves due to exhaustion.

According to SCB (Statistics Sweden), the numbers of employees in simple office work at year 2010 were more than 230 000 persons in Sweden. The estimated costs for a 2 percent loss in performance for the society would then become around 2 164 000 000 Swedish crowns/year (around 257 000 000 Euro/year) due to background noise.

Restoration and some practical implications

So far, many environments have just been studied with regard to their visual value for restoration. Paper I and Paper II showed, however, that the sound conditions during a short break mattered, both for ratings of energy and motivation. The best break condition turned out to be when watching a nature movie with sounds (or without sounds – Paper II) and the worst condition was to be exposed to office noise.

The content of the breaks applied in these experimental studies may be questioned for the relevance to real office life. It is probably of better practical use to visit a real nature environment than to watch a nature movie, for example in the coffee room. However, in real office life the coffee rooms might be noisy and some employees bring their coffee back to a noisy office desk, pointing towards the importance of gaining more knowledge about the restorative effects of sounds. It is, however, not only important to gain knowledge on how the sound atmosphere can influence the restorative outcomes at work. The noise conditions in other environments visited for restorative purposes need also further attention (e.g., a park).

As little is known about which cognitive processes are actually fatigued with prolonged and intensive work, it is interesting to note that Paper II showed that the processes involved in counting were restored after watching the nature movie (i.e., for normal hearing participants), even though it is not a pure measure of attention/inhibition. Consequently, it might not (only) be an attention mechanism that gets fatigued, as suggested by ART. It is, however, a risk that the results of Paper II are underpowered due to the small sample size. No other measures

applied in Paper I or II indicated a change in performance after the breaks. This is in line with earlier studies, showing that the most support for ART comes from self-ratings and not from actual performance measures of attention/inhibition. However, when no effect is found, it is also difficult to rule out if this was due to the length and weakness of the break manipulation, or the insensitivity of the cognitive process/measure.

I hope that this thesis can be a motivator for further investigations of multi-modal restoration and a better organization of the measures of cognitive restoration processes in future research.

Methodological limitations

There are several limitations with the current work, however, only some of the main concerns will be brought up here. In the first two papers we tried to simulate an open-plan office in our laboratory with open-plan office noise played back by hidden loudspeakers on the walls. The sound was recorded in an actual open-plan office in Sweden, however, their ecological validity can be questioned. We cannot, for example, tell if the replayed sound at different directions gives the same effects as actual sounds. However, several participants reported that they had to look over the shoulder when it sounded like someone passed by behind them, which points towards a realistic experience. Further, the sound we used was recorded in an open-plan office with about 30 employees but the day when the sound was recorded showed up to be a day when most of the workers were out of office. Therefore, the office was quite calm with about 5-8 peaceful voices heard. We added some more phones and voices to the file but there were still several quiet parts. The rather calm and moderately energetic employees in this sound file points towards an underestimation of the noise effects rather than an overestimation. However, the tested sound is from only one open-plan office in Sweden and is not representative for the noise situation in all open-plan offices.

Moreover, in Paper I there was a major problem with order effects regarding the presentation of sessions. Participants' performance changed depending on whether they had been exposed to a high or low noise condition in the previous session. We tried to repair this in Paper II by including a longer practice session before the real sessions. This was a way to reduce possible training effects already before the first session, however, the session order effects appeared also in Paper II. The session order effects made it necessary to change the within-person design to a between-person design for the cognitive measures. However, sample sizes were not intended for this unexpected design change. Therefore we got a loss in

power, which made it more difficult to detect real effects (i.e., increased probability of Type II error).

Throughout the different studies we have used a variety of cognitive measures. Several of them are theoretically generated and their ecological validity is not clear. Overall it has also been difficult to distinguish the tasks and define the attributes or processes involved, which was evident in Paper III and Paper IV. It has also been difficult to adjust the level of difficulty of the tasks to the participants, as floor and ceiling effects were evident for some tasks. The cognitive capacity seemed to vary between samples and participants. We have, however, not considered how the individual differences in working memory capacity (WMC) may have modulated the noise effects. There are studies showing that high-WMC individuals can suppress irrelevant stimuli to a higher degree, as they presumably are more able to engage attentional resources in the focal task, and especially if the task requires high cognitive load (Sörqvist, Stenfelt & Rönnberg, 2012).

Further, in the current work the effects of office noise have been tested with exposure times between 1-2 hours. We cannot say whether the present results would change with a longer exposure time and whether it is possible to habituate to office-noise during a longer exposure time, such as for people who work in open-plan offices for weeks or months. According to Banbury and Berry (1997) it may be possible to habituate to speech after a 20 minutes exposure, however, after only a few minutes of quiet the effect of the sound is reestablished. Basic research has further indicated that it is possible to habituate to deviants (Sörqvist, Nöstl & Halin, 2012), especially for individuals with high WMC, but not to the irrelevant sound effect (Tremblay & Jones, 1998). This may come from that it is possible to cognitively control and direct your attention away from deviants, while the processing of irrelevant sound is more automatically driven (Sörqvist, 2010).

Some caution should also be applied when drawing conclusions from the current studies of cognitive restoration, especially since training and motivational effects are difficult to distinguish from fatigue effects. It is also difficult to clarify if a lack of an effect is due to the insensitivity of the cognitive process/measure, or the duration and weakness of the restorative manipulation.

Future research directions

Further research is needed to investigate a greater variety of open-plan office settings (i.e., acoustic surroundings) and tasks with different attributes. For instance, more knowledge is needed according to what is the best combination of reduced noise level, speech intelligibility

and intermittent sounds to enhance performance, and further, how the office should be designed to reach the new target values.

The present studies can serve as a good platform for further investigations (i.e., with more STI-values and tasks) of the Hongisto´s (2005) model of the STI - performance function. The findings would provide further details of the shape of the curve and the amount of performance decrement for tasks varying in content and complexity.A way to proceed is also to try out some of the tasks in an actual open-plan office.

So far, much of the focus within this field of research has been on different types of noise and layouts of the office. However, personal characteristics, other than hearing status, should also be addressed. For example, individual differences in WMC and how cognitive control moderates auditory distraction and habituation to office noise. Nonetheless, it is important to conclude that it is not just the reduction of negative aspects in the work environment that needs consideration, we also need to find ways to promote aspects that can have a positive impact on the employees, including the possibilities for recovery.

So far little attention has been brought to the importance of providing good restorative environments for the employees to maintain concentration and well-being throughout the day. This is especially true for multi-modal restoration. Future research need to examine whether pleasant visual stimuli or sounds during the break, or both, can promote restorative experiences also outside the experimental setting.

Conclusion

Open-plan office noise can have a negative impact on fatigue, motivation and performance. How much performance is impaired appears to vary with hearing status and the cognitive processes required by the tasks performed. Yet, research is needed to find the best combination of reduced sound level, speech intelligibility and intermittent sounds to enhance performance. In addition, it is important to pay attention to the environments visited for restoration, as noise exposure during a break can further decrease motivation and subsequent performance.

Funding body

The research in this thesis was mainly supported by a grant from AFA Insurance to Staffan Hygge (070112). Support in the form of sound insulation material and furniture for the office setting were provided by Ecophon and S-line office.

Svensk sammanfattning

I denna avhandling presenteras fyra experimentella studier (i fyra artiklar) med det övergripande syftet att undersöka effekter av kontorsbuller på kognitiv prestation och återhämtning. I de första två artiklarna fokuserades effekter av olika ljudnivåer på prestation, trötthet och stress. I de två sista artiklarna var fokuseringen mer direkt på effekterna av bakgrundstal, eftersom tidigare studier har visat att talljud är den mest störande bullerkällan i öppna kontorslandskap. Resultaten från Artikel I visade på en försämrad prestation i ordminne, ökad trötthet och brister i motivation när bakgrundsnivån ökade med 12 dB (39 till 51 dB LAeq). Vidare visade Artikel II att ljudnivåeffekterna var mer utpräglade för personer med hörselnedsättning.

När det gäller effekter av irrelevant tal visade Artikel III att den kognitiva prestationen försämrades som en funktion av taluppfattbarhet, ju bättre taluppfattbarhet - mätt med *Speech Transmission Index* (STI) - desto sämre prestation. Resultaten indikerade att STI-värdet måste vara mindre än 0,50 för att ha en gynnsam inverkan på prestationen. Vidare visade både Artikel III och IV att prestationen försämras mer av bakgrundstal om arbetsuppgiften kräver episodiskt minne och/eller processer av repetition - t.ex. vid informationssökning och när ord behöver memoreras. Intressant var även att vissa uppgifter var okänsliga för bakgrundstal. Oväntat framkom inga effekter av den relativt kortvariga exponeringen av kontorsbuller på deltagarnas utsöndring av stresshormoner (Artikel I och Artikel II).

Effekterna av en paus behandlades i Artikel I och II. Pausen var inlagd direkt efter arbetspassen i buller och hade olika innehåll för deltagarna. Artikel I visade att en paus med en naturfilm med motsvarande naturljud ökade energiskattningarna jämfört med att bara få lyssna på porlande vatten eller kontorsbuller. Vidare blev motivationsskattningarna lägst vid fortsatt exponering för kontorsbuller under pausen. Artikel II visade även på förbättrad räkneförmåga och motivation efter en paus med en naturfilm och försämrad prestation och motivation efter fortsatt bullerexponering. För deltagarna med hörselnedsättning ökade motivationen och prestationen efter pausen med buller, men inte efter att ha sett naturfilmen.

Sammantaget visar denna avhandling att kontorsbuller kan ha en negativ inverkan på trötthet, motivation och prestation. Hur mycket prestationen försämras förefaller att variera med de kognitiva processer som fordras av uppgiften och med hörsel status. Dessutom kan fortsatt bullerexponering under en kort paus minska motivationen och försämra den efterföljande prestationen ytterligare.

References

Alvarsson, J., Wiens, S., & Nilsson, M.E. (2010). Stress recovery during exposure to nature sound and noise. *International Journal of Environmental Research and Public Health, 7,* 1036-1046.

Arbetsmiljöverket [*The Swedish Work Environment authority]* (2005). Arbetsmiljöverkets författningssamling [*Statutes of The Swedish Work Environment Authority*]. Solna (Sweden): Arbetsmiljöverket, Publikationsservice.

Arlinger S. (1999). Störning av talkommunikation [*Disturbance of spoken communication*]. In U. Landström, S. Arlinger, S. Hygge, Ö. Johansson, A. Kjellberg & K. Persson Waye (Eds.), *Störande buller, kunskapsöversikt för kriteriedokumentation* [*Disturbing noise, review for criteria documentation*]. Stockholm: National Institute of Working Life.

Babisch, W. (2003). Stress hormones in the research on cardiovascular effects of noise. *Noise & Health, 5*, 1-11.

Banbury, S., & Berry, D.C. (1997). Habituation and dishabituation to speech and office noise. *J Exp Psychol Appl, 3*, 181–195.

Banbury, S., & Berry, D.C. (1998). Disruption of office-related tasks by speech and office noise. *British Journal of Psychology, 89*, 499-517.

Bengtsson, J. (2003). *Low frequency noise during work – effects on performance and annoyance*. Doctoral thesis, comprehensive summary. Gothenburg: Göteborg University.

Berman, M.G., Jonides, J., & Kaplan, S. (2008). The cognitive benefits of interacting with nature. *Psychological science, 19*, 1207-1211.

Berman, M.G., Kross, E., Krpan, K.M., Askren, M.K., Bruson, A., Deldin, P.J., Kaplan, S., Sherdell, L., Gotlib, I.H., & Jonides, J. (2012). Interacting with nature improves cognition and affect for individuals with depression. *Journal of Affective Disorders, 140*, 300–305.

Berto, R. (2005). Exposure to restorative environments helps restore attentional capacity. *Journal of Environmental Psychology, 25*, 249-259.

Bodin, M., & Hartig, T. (2003). Does the outdoor environment matter for psychological restoration gained through running?. *Psychology of Sport and Exercise, 4*, 141-153.

Boman, E., Enmarker, I., & Hygge, S. (2005). Strength of noise effects on memory as a function of noise source and age. *Noise & Health, 7*, 11-26.

Colle, H.A. (1980) Auditory encoding in visual short-term recall: effects of noise intensity and spatial location, *J Verbal Learn Verbal Behav, 19*, 722–735.

Cowan, N. (1995). *Attention and memory: An integrated framework*. Oxford, England: Oxford University Press.

Danielsson, C.B. (2010). *The office - an explorative study: architectural design's impact on health, job satisfaction & well-being*. Doctoral thesis, comprehensive summary. Stockholm: The Royal Institute of Technology.

Ellermeier, W., & Hellbrück, J. (1998). Is level irrelevant in "irrelevant speech"? Effects of loudness, signal-to-noise ratio, and binaural unmasking. *Journal of Experimental Psychology, 24*, 1406-1414.

Evans, G.W., Bullinger, M., & Hygge, S. (1998). Chronic noise exposure and physiological response: a prospective study of children living under environmental stress. *Psychological Science, 9*, 75-77.

Evans, G.W., & Johnson, D. (2000). Stress and open-office noise. *Journal of Applied Psychology, 85*, 779-783.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: a latent-variable analysis. *Journal of Experimental Psychology, 133*, 101-135.

Gidlöf-Gunnarsson, A., & Öhrström, E. (2007). Noise and well-being in urban residential environments: the potential role of perceived availability to nearby green areas. *Landscape and Urban Planning, 83*, 115-126.

Glass, D.C., & Singer, J.E. (1972). *Urban stress: experiments on noise and social stressors*. Academic Press, New York.

Haka, M., Haapakangas, A., Keränen, J., Hakala, J., Keskinen, E., & Hongisto, V. (2009). Performance effects and subjective disturbance of speech in acoustically different office types - a laboratory experiment. *Indoor Air, 19*, 454-467.

Harris, J.D. (1953). A brief critical review of loudness recruitment. *Psychological Bulletin, 50,190*-203.

Hartig, T., Böök, A., Garvill, J., Olsson, T., & Gärling, T. (1996). Environmental influences on psychological restoration. *Scandinavian Journal of Psychology, 37*, 378-393.

Hartig, T., Evans, G. W., Jamner, L. D., Davis, D. S., & Gärling, T. (2003). Tracking restoration in natural and urban field settings. *Journal of Environmental Psychology, 23*, 109-123.

Hartig, T., & Jahncke, H. (2012). Conceptual and methodological issues in restorative environments research. [in preparation].

Hartig, T., Mang, M., & Evans, G. W. (1991). Restorative effects of natural environment experiences. *Environment and Behavior, 23*, 3-26.

Health Council of the Netherlands (2004). *Nature and health. The influence of nature on social, psychological and physical well-being*. Publication no. 2004/09. The Hague: Health Council of the Netherlands and Dutch Advisory Council for Research on Spatial Planning, Environment and Nature.

Helenius, R., & Hongisto, V. (2004). The effect of acoustical improvement of an open-plan office on workers. *Published in the Proceedings of InterNoise, August 21-25* (Paper 674). Prague, Czech Republic.

Hongisto, V. (2005). A model predicting the effect of speech of varying intelligibility on work performance, *Indoor Air, 15*, 458-468.

Hongisto, V. (2008). Effects of sound masking on workers – a case study in a landscape office. In: Griefahn, B. (Ed.). *Published in the Proceedings of ICBEN 2008, the 9th Congress of the International Commission on the Biological Effects of Noise*. Connecticut, USA.

Hughes, R.W., Vachon, F., & Jones, D.M. (2007). Disruption of short-term memory by changing and deviant sounds: support for a duplex-mechanism account of auditory distraction. *J Exp Psychol Learn Mem Cogn, 33*, 1050-61.

IEC 60218-16 (2003). Sound system equipment — Part 16: Objective rating of speech intelligibility by speech transmission index. International Organization for Standardization, Genève, Switzerland.

ISO standard 3382-3 (2012). Acoustics — Measurement of room acoustic parameters — Part 3: Open-plan offices. International Organization for Standardization, Genève, Switzerland.

Jahncke, H., Eriksson, K., & Naula, S. (2012). Shall we silence cities and workplaces?: the effects of auditive and visual stimuli on perceived restoration likelihood. *Published in the Proceedings of InterNoise, 41st International Congress and Exposition on Noise Control Engineering, August 19-22*. New York City, USA.

James, W. (1892). *Psychology: The briefer course*. New York: Holt.

Jiang, B, Liebl, A., Leistner, P., & Yang, J. (2012). Sound masking performance of time-reversed masker processed from the target speech. *Acta Acustica united with Acustica, 98*, 135-141.

Johansson, B. (2002). *Buller och bullerbekämpning.* Stockholm: Arbetsmiljöverket.

Jones, D.M., & Davies, D.R. (1984) Individual and group differences in the response to noise. In: D.M. Jones & A.J. Chapman (Eds.), *Noise and society*. Chichester: Wiley.

Jones, D.M., & Morris, N. (1992). Irrelevant speech and serial recall: implications for theories of attention and working memory. *Scandinavian Journal of Psychology, 33*: 212-229.

Kaarlela-Tuomaala, A., Helenius, R., Keskinen, E., & Hongisto, V. (2009). Effects of acoustic environment on work in private office rooms and open-plan offices - longitudinal study during relocation, *Ergonomics, 52*, 1423-1444.

Kaplan, R., & Kaplan, S. (1989). *The experience of nature: A psychological perspective.* New York: Cambridge University Press.

Kaplan, S. (1995). The restorative benefits of nature: towards an integrative framework. *Journal of Environmental Psychology, 15*, 169-182.

Keighley, E. C., & Parkin, P. H. (1979). Subjective response to sound conditioning in a landscaped office. *Journal of Sound and Vibration, 64*, 313-323.

Keränen, J., Hongisto, V., Hakala, J., & Oliva, D. (2011). Speech privacy in an open-plan office with different room acoustic conditions, *Published in Forum Acusticum* (paper 135), 27 June - 1 July, Aalborg, Denmark.

Kjellberg, A. (1997). Noise. In H. A. Waldron, & C. Edling (Eds.), *Occupational health practice* (4th edition). (pp. 241-256). Oxford: Butterworth Heinemann.

Kjellberg, A. (1999). Bullerstörning utifrån bullrets fysikaliska egenskaper (*Swedish*) In U. Landström, S. Arlinger, S. Hygge, Ö. Johansson, A. Kjellberg & K. Persson Waye (Eds.), *Störande buller, kunskapsöversikt för kriteriedokumentation* [Disturbing noise, review for criteria documentation]. Stockholm: National Institute of Working Life.

Kjellberg, A., & Landström, U. (1994) Noise in the office: Part II. - The scientific basis (knowledge base) for the guide. *International Journal of Industrial Ergonomics, 14*, 93–118.

Kjellberg, A., Muhr, P. & Sköldström, B. (1998) Fatigue after work in noise – an epidemiological survey study and three quasi-experimental field studies. *Noise and Health, 1*, 47-55.

Kjellberg, A., & Sköldström, B. (1991). Noise annoyance during the performance of different nonauditory tasks. *Perceptual and Motor Skills, 73*, 39-49.

Kjellberg, A., & Wide, P. (1988). Effects of simulated ventilation noise on performance of a grammatical reasoning task. In: B. Berglund, U. Berglund, J. Karlsson and T. Lindvall (Eds.), *Published in the Proceedings of the 5th International Congress on Noise as a Public Health Problem*, Vol. 3. Byggforskningsrådet, Stockholm, Sweden.

Kristiansen, J., Mathiesen, L., Nielsen, P. K., Hansen, A. M., Shibuya, H., Petersen, H. M., et al. (2008). Stress reactions to cognitively demanding tasks and open-plan office noise. *International Archives of Occupational and Environmental Health, 82*, 631-641.

Landström, U. (1999). Bullerstörning utifrån bullrets fysikaliska egenskaper (*Swedish*) In U. Landström, S. Arlinger, S. Hygge, Ö. Johansson, A. Kjellberg & K. Persson Waye (Eds.), *Störande buller, kunskapsöversikt för kriteriedokumentation* [Disturbing noise, review for criteria documentation]. Stockholm: National Institute of Working Life.

Landström, U., Byström, M., & Nordström, B. (1985). Changes in wakefulness during exposure to noise at 42 Hz, 1000 Hz and individual EEG frequencies. *J Low Freq Noise Vibr, 4*, 27-33.

Laumann, K., Gärling, T., & Stormark, K.M. (2003). Selective attention and heart rate responses to natural and urban environments. *Journal of environmental psychology, 23*, 125-134.

Lethbridge, K., Yankou, D., & Andrusyszyn, M-A. (2005). The effects of a restorative intervention on undergraduate nursing students' capacity to direct attention. *J Holist Nurs, 23*, 329-347.

Ljung, R., & Kjellberg, A. (2009). Long reverberation time decreases recall of spoken information. *Building Acoustics, 16*, 301-311.

Lowen, L.J., & Suedfelt, P. (1992). Cognitive and arousal effects of masking office noise. *Environment & Behavior, 24*, 381-395.

Lundberg, U., & Frankenhaeuser, M. (1978) Psychophysiological reactions to noise as modified by personal control over noise intensity. *Biological Psychology, 6*, 51-59.

Marsh, J.E., & Jones, D.M. (2010). Cross-modal distraction by background speech: what role for meaning? *Noise Health, 12*, 210-216.

Marsh, J.E., Hughes, R.W., & Jones, D.M. (2008). Auditory distraction in semantic memory: a process-based approach. *J Mem Lang, 58*, 682-700.

Marsh, J.E., Hughes, R.W., & Jones, D.M. (2009) Interference by process, not content, determines semantic auditory distraction. *Cognition, 110*, 23-38.

Melamed, S., & Bruhis, S. (1996). The effects of chronic industrial noise exposure on urinary cortisol, fatigue and irritability: a controlled field experiment. *J Occup Environ Med, 38*, 252-256.

Milczarek, M., Schneider, E., & González, E. (2009). *OSH in figures: Stress at work – facts and figures*. Luxemburg.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., &Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cognitive Psychology, 41*, 49-100.

Moore, B.C. (2003). Speech processing for the hearing-impaired: success, failures, and implications for speech mechanisms. *Speech Commun, 41*, 81-91.

Naveh-Benjamin, M., Craik, F.I.M., Perretta, J.G., & Tonev, S.T. (2000). The effects of divided attention on encoding and retrieval processes: the resiliency of retrieval processes. *The Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology, 53*, 609-625.

Neely, C.B., & LeCompte, D.C. (1999). The importance of semantic similarity to the irrelevant speech effect. *Mem Cognit, 27*, 37-44.

Perham, N., & Banbury, S. (2012). The role of rehearsal in a novel call center-type task. *Noise & Health, 14*, 1-5.

Perham, N., Marsh, J.E., & Jones, D.M. (2009). Syntax and serial recall: how language support short-term memory for order. *Q J Exp Psychol,62*, 1285-91.

Persson, J., Welsh, K.M., Jonides, J., & Reuter-Lorenz, P.A. (2007).Cognitive fatigue of executive processes: interaction between interference resolution tasks, *Neuropsychologia, 45*, 1571–1579.

Persson-Waye, K., Bengtsson, J., Rylander, R., Hucklebridge, F., Evans, P., & Clow, A. (2002). Low frequency noise enhances cortisol among noise sensitive subjects during work performance. *Life Sciences, 70*, 745-758.

Raanaas, R.K., Horgen, K.E., Rich, D., Sjøstrøm, G., & Patil, G. (2011). Benefits of indoor plants on attention capacity in an office setting. *Journal of Environmental Psychology, 31*, 99–105.

Salamé, P., & Baddeley, A. (1982) Disruption of short-term memory by unattended speech: implications for the structure of working memory, *J Verbal Learn Verbal Behav, 21*, 150-64.

Schlittmeier, S., Hellbrück, J., Thaden, R., & Vorländer, M. (2008). The impact of background speech varying in intelligibility: effects on cognitive performance and perceived disturbance. *Ergonomics, 51*, 719-736.

Shelton, J.T., Elliott, E.M., Lynn, S.D., & Exner, A.L. (2009).The distracting effects of a ringing cell phone: an investigation of the laboratory and the classroom setting. *Journal of Environmental Psychology, 29*, 513–521.

Smith-Jackson, T. L., & Klein, K. W. (2009). Open-plan offices: task performance and mental workload. *Journal of Environmental Psychology, 29*, 279-289.

Soames Job, R.F. (1999). Noise sensitivity as a factor influencing human reaction to noise. *Noise & Health, 1*, 57-68.

Sundstrom, E., Town, J.P., Rice, R.W., Osborn, D., & Brill, M. (1994). Office noise, satisfaction, and performance. *Environment & Behavior, 26*, 195-222.

Swedish Standard, SS 25268 (2007). "Byggakustik - Ljudklassning av utrymmen i byggnader - Vårdlokaler, undervisningslokaler, dag- och fritidshem, kontor och hotell" [*Acoustics - Sound classification of spaces in buildings - Institutional premises, rooms for education, preschools and leisure-time centres, rooms for office work and hotels*]. Swedish Standards Institute, Stockholm, Sweden.

Szalma, J.L., & Hancock, P.A. (2011). Noise effects on human performance: a meta-analytic synthesis. *Psychological Bulletin, 137*, 682-707.

Sörqvist, P. (2010). *The Role of Working Memory Capacity in Auditory Distraction*. Doctoral thesis, comprehensive summary. Luleå: Luleå university of Technology.

Sörqvist, P., Nöstl, A., & Halin, N. (2012). Working memory capacity modulates habituation rate: Evidence from a cross-modal auditory distraction paradigm. *Psychonomic Bulletin & Review, 19*, 245-259.

Sörqvist, P., Stenfelt, S., & Rönnberg, J. (2012). Working memory capacity and visual-verbal cognitive load modulate auditory-sensory gating in the brainstem: towards a unified view of attention. *Journal of Cognitive Neuroscience*. [Accepted].

Tafalla, R., & Evans, G. W. (1997). Noise, physiology, and human performance: the potential role of effort. *Journal of Occupational Health Psychology, 2*, 148-155.

Tremblay, S., & Jones, D.M. (1998). Role of habituation in the irrelevant sound effect: evidence from the effects of token set size and rate of transition. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 24*, 659-671.

Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology, 11*, 201-230.

Veitch, J.A., Bradley, J.S., Legault, L.M., Norcross, S., Svec, J.M. (2002). *Masking speech in open-plan offices with simulated ventilation noise: noise level and spectral composition effects on acoustic satisfaction* (IRC-IR-846). National research council Canada: Institute for research in construction.

Venetjoki, N., Kaarlela-Tuomaala, A., Keskinen, E., & Hongisto, V. (2006). The effect of speech and speech intelligibility on task performance, *Ergonomics*, *49*, 1068-1091.

Virjonen, P., Keränen, J., Helenius, R., Hakala, J., & Hongisto, V. (2007). Speech privacy between neighboring workstations in an open office - a laboratory study. *Acta Acustica united with Acustica, 93*,771-782.

Virjonen, P., Keränen, J., & Hongisto, V. (2009).Determination of acoustical conditions in open-plan offices - Proposal for new measurement method and target values. *Acta Acustica united with Acustica, 95*, 279-290.

Åhsberg, E., Gamberale, F., & Kjellberg, A. (1995). Upplevd trötthetskvalitet vid olika arbetsuppgifter. Utveckling av ett mätinstrument. [*Perceived fatigue quality during different work tasks. Development of a measure*]. Solna (Sweden): Arbetsmiljöinstitutet. Nr. 20.

Paper I

Journal of Environmental Psychology 31 (2011) 373–382

Contents lists available at ScienceDirect

Journal of Environmental Psychology

journal homepage: www.elsevier.com/locate/jep

Open-plan office noise: Cognitive performance and restoration

Helena Jahncke [a,*], Staffan Hygge [a], Niklas Halin [a], Anne Marie Green [a], Kenth Dimberg [b]

[a] Environmental Psychology, Faculty of Engineering and Sustainable Development, University of Gävle, SE-801 76 Gävle, Sweden
[b] Department of Electronics, Mathematics and Natural Sciences, Faculty of Engineering and Sustainable Development, University of Gävle, Sweden

ARTICLE INFO

Article history:
Available online 2 August 2011

Keywords:
Working memory
Emotion
Physiology
Open-plan office
Stress

ABSTRACT

The aim of the present study was to investigate cognitive, emotional, and physiological effects of two open-plan office noise conditions (high noise: 51 LAeq and low noise: 39 LAeq) during work in a simulated open-plan office, followed by four restoration conditions (river movie with sound, only river sound, silence, and office noise) after the work period. Students (N = 47) went through one practice session and two experimental sessions, one each with the low and high noise conditions. In each experimental session they worked for 2 h with tasks involving basic working memory processes. We also took physiological measures of stress (cortisol and catecholamines) and self-reports of mood and fatigue. Analyses indicate that the participants remembered fewer words, rated themselves as more tired, and were less motivated with work in noise compared to low noise. In the restoration phase the participants who saw a nature movie (including river sounds) rated themselves as having more energy after the restoration period in comparison with both the participants who listened to noise and river sounds. Remaining in office noise during the restoration phase also affected motivation more negatively than listening to river sounds or watching the nature movie. The findings bear on the appropriateness of open-plan office designs and the possibilities for restoration available in office settings.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Research has often reported lower satisfaction, lower work productivity, and poorer health among the employees working in open-plan offices compared to traditional offices (see reviews by Navai & Veitch, 2003; Oommen, Knowles, & Zhao, 2008; Rashid & Zimring, 2008). Research has also indicated that the majority of the negative effects seem to be associated with an increase in background noise and ensuing distraction (Hedge, 1982). The results are, however, mainly from studies in field settings with self ratings of different work conditions rather than from laboratory studies with controlled conditions and objective measures of cognitive performance and acute stress effects (see review by De Croon, Sluiter, Kuijer, & Frings-Dresen, 2005). Such studies can also aid the understanding of different sub-processes within working memory activated with office work. Such studies can also address relatively little studied issues concerning methods for recovery from work in office settings.

In the present experimental study we approached two main issues concerning open-plan offices. First we examined the effects of noise on basic working memory processes, self-ratings (mood and fatigue) and physiological measures of stress (saliva and urine samples). Second, we examined the effects of varying sound conditions on restoration at work.

1.1. Office noise effects on working memory and stress

Working memory (WM) processes are of crucial importance when working with complex tasks because they process information necessary for the task at hand and temporarily store and handle the needed information. WM has a limited capacity (Baddeley, 2002) and performance can decline if a task is performed in competing background noise (Banbury, Macken, Tremblay, & Jones, 2001; Jones, 1990; Sörqvist, Halin, & Hygge, 2009).

Noise appears to affect different WM tasks in different ways. For example, noise (such as irrelevant speech) impairs performance in proofreading (e.g., Smith-Jackson & Klein, 2009; Venetjoki, Kaarlela-Tuomaala, Keskinen, & Hongisto, 2006), serial recall (for a review, see Jones & Morris, 1992), mental arithmetic (e.g., Banbury & Berry, 1998; Schlittmeier, Hellbrück, Thaden, & Vorländer, 2008), reading comprehension (REFS), operation span, and tasks activating prior knowledge from long-term memory (Haka et al., 2009). Even if the majority of these tasks involved memory and seriation at some point (encoding and/or rehearsal), the studies particularly

* Corresponding author. Tel.: +46 26 64 81 24.
E-mail address: helena.jahncke@hig.se (H. Jahncke).

0272-4944/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvp.2011.07.002

interested in the effects of open office noise have mainly taken a macro perspective on working memory. According to Roper and Juneja's (2008) categorization, only three of the 59 studies they reviewed included tasks which measure the subsystems of working memory and only five studies included tasks which measure the earlier unitary model of short-term memory. Thus, there is a need for further applied noise studies which make use of the different measures recently developed in working memory research.

One way to approach and investigate how WM is affected by noise applies the well known multicomponent model of working memory (Baddeley & Hitch, 1974; further developed by Baddeley, 2000). According to this model there are two modality-specific stores handling verbal or visual stimuli (i.e., the articulatory loop and the visuo-spatial sketchpad, respectively), together with one episodic buffer capable of multidimensional coding and one executive function that controls the other subsystems.

Another approach does not include modality-specific buffers such as the articulatory loop. Instead the focus is on the limited capacity of working memory and how a set of integrated processes can get disturbed by noise (Just & Carpenter, 1992). In the present study working memory will mainly be seen from different measures that have been developed to tap the integrated processes involved in complex tasks, rather than through further investigation of the hypotheses of working memory.

Earlier studies have indicated that task difficulty is important for the degree of disturbance by noise (e.g. Kjellberg & Sköldström, 1991), and depending on which task is performed, there seem to be different executive functions involved. Results from Miyake et al. (2000) suggest that updating (the ability to update information in WM), shifting (the ability to shift between mental sets) and inhibition (the ability to inhibit responses) are moderately correlated but clearly separable functions, and that it is possible to distinguish them according to their relative contribution to performance in complex tasks. We therefore employed tasks developed to tap these three basic functions, to explore whether these functions are differentially affected by office noise.

Further research (e.g., Friedman & Miyake, 2004) has also suggested that there are at least two inhibition mechanisms that must be distinguished. The first mechanism is *response inhibition*, which inhibits motor responses or distracting stimuli and can be tapped by tasks such as the Stroop task (e.g., Venetjoki et al., 2006), the Flanker task (e.g., Heitz & Engle, 2007) and the Sustained Attention to Response Test (SART; e.g., Manly, Robertson, Galloway, & Hawkins, 1999). The second mechanism is *cognitive inhibition*, which inhibits no-longer relevant information that was once activated in working memory and can be tapped by tasks that involve proactive interference (PI; e.g. Lustig, May, & Hasher, 2001). Therefore, tasks related to each of these mechanisms (i.e., SART and PI) were included in the present investigation of fatigue- and office noise effects.

Only a small number of studies have reported objective physiological assessments of the acute stress effects of office noise. These studies have mainly used measures of stress hormones, heart rate variability, blood pressure and activity in the trapezius muscles (e.g., Evans & Johnson, 2000; Kristiansen et al, 2008; Sloan, 1991; Waye et al., 2002). We were also interested in finding out whether our acute office noise exposure would show up in physiological measures, and whether physiological reactions mediate effects on cognitive performance during exposure to office noise. Hence, we include urine- and saliva samples to measure the changes in stress hormone production.

1.2. Restoration

If stress increases and performance declines while working in office noise, the question arises whether these changes can be moderated if a short restoration period is included, and whether the ensuing changes vary with the content of the restorative period.

Studies of restoration have mainly shown that nature environments are restorative to be in or to look at when cognitively fatigued (e.g., Berto, 2005; Hartig, Böök, Garvill, Olsson, & Gärling, 1996). These studies focused on the *visual* perception of the environment and not on the *sound* conditions per se. There are, however, some results indicating faster and more complete restoration (according to both performance and physiological measures) for participants exposed to nature movies with environmental sounds, in comparison to those exposed to other environments including sounds (Laumann, Gärling, & Stormark, 2001, 2003; Ulrich et al., 1991). Some studies have also shown a restorative advantage of natural versus urban settings in field conditions that included the sounds typical of each type of environment (Berman, Jonides, & Kaplan, 2008; Hartig, Evans, Jamner, Davis, & Gärling, 2003; Hartig, Mang, & Evans, 1991).

Khalfa, Bella, Roy, Peretz, and Lupien (2003) have also shown the restorative effects of positive sounds only. They compared recovery from sitting in silence with listening to soft music, and found that music promoted faster decline in salivary cortisol, measured after 15 min into the relaxation period. However, no studies (to the authors' knowledge) have investigated whether positive nature sounds by themselves can promote restoration and ensuing cognitive performance.

1.3. Aims and hypotheses

The aims of the present study thus were to further specify how noise in open-plan offices affects cognitive performance and acute stress, and to test whether it is possible to promote cognitive restoration with exposure to pleasant sounds and film-clips of pleasant nature environments after having been exposed to aversive sounds. Our hypotheses are as follows:

Hypothesis 1. Participants' *cognitive performance* will decrease more in high noise compared to low noise.

Hypothesis 2. Participants will have a larger increase of *stress hormones* from before to after the work session in high noise compared to low noise.

Hypothesis 3. Participants' *self ratings* of tiredness and motivation will decrease more with work in high noise compared to low noise.

Hypothesis 4. Participants will *restore* from fatigue (measured as performance on cognitive tasks, self ratings and cortisol levels) to differing degrees as a function of environmental conditions, including sound variations. More precisely, we expect the following order of restorativeness: a nature movie with nature sounds (positive stimuli for two senses), just nature sounds (positive stimuli for one sense), silence (no stimuli) and noise (negative stimuli).

2. Method

2.1. Design

To test these hypotheses we designed an experiment with two acoustic environments (low noise, high noise) varied within subjects and four restorative conditions (nature movie, nature sound, silence, noise) manipulated between subjects.

2.2. Participants

The participants were 47 persons with normal hearing and vision recruited from the University of Gävle (27 female; mean

age = 26). Participants were informed of the study's nature and risks before participating and they were randomly assigned to conditions. Participation in all sessions of the experiment was compensated with 990 Swedish crowns.

2.3. Research setting

The research was carried out in an office laboratory (63 m^2) at the University of Gävle (Fig. 1). The room was designed to simulate a neutral open-plan office including windows to a white room with simulated outdoor lighting.

The workstations were separated with 1.43 m high screens. Each cubicle was 1.24 m wide. At each end of the set of cubicles a pane of glass was installed to better avoid direct sounds from the loudspeakers to the participants sitting close by. Behind the participants on each side were also 3.60 m wide × 1.80 m high screens to better avoid direct sounds from the loudspeakers behind.

Ambient conditions in the indoor environment were fairly constant throughout the experiments. The room temperature at the work place varied between 20.7 and 21.6 °C during the experimental sessions. The airflow was 20 l/s for each person in the experiment, and the CO_2 concentration was always well below 1000 ppm. Luminance was set to 480–520 lx incident on the height of the seating in each work station and met the current recommendations in Sweden for work with computers (SS-EN 12464-1, 2003). The luminance in the room outside the window was set to 1950 lx measured at the middle of the window.

2.4. Noise conditions

The noise used in the experiment was recorded in four positions in an actual open-plan office in Sweden. From the multi-channel recording, 1 h of office noise was extracted and edited and reproduced in the test room with eight loudspeakers, two at each wall, and one subwoofer. Two noise conditions were designed, one with a high- and one with a low noise level. In the high noise condition, additional phone and speech signals were added to the office noise. The phone signals consisted of different mobile tunes and stationary telephones ringing. The speech signals were conversations recorded from radio, from which we cut away one of the voices to simulate telephone conversations. The noise was reproduced with an equivalent A-weighted sound pressure level (L_{Aeq}) of 51 dBA in the room, since a common noise level for open-plan offices is around 50 dBA (Venetjoki et al., 2006). In the low noise condition, the office noise, including the additional phone and speech signals, was reduced L_{Aeq} in the room by 12–39 dBA. The filter was used to check if noise levels reduced by a wall screen would give positive effects in open-plan offices. The 1 h office noise tape was looped once, and the sound signals in the latter hour were rotated 180° to equalize noise exposure throughout the room. The phone and speech signals in the high noise condition were added independently to each 1 h sequence but were balanced in terms of level, duration and frequency.

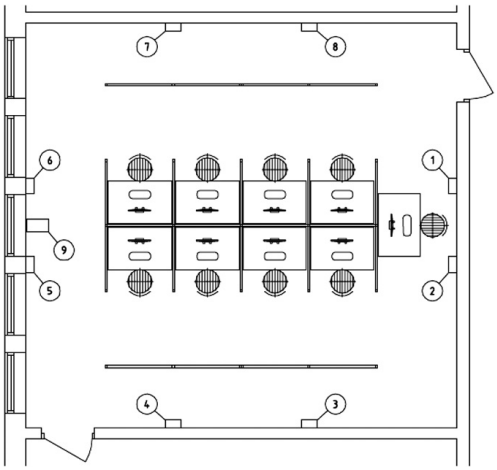


Fig. 1. The simulated open-plan office contained eight workstations. The noise was played back from 8 loudspeakers (1–8) and one subwoofer (9). The experimental leader sat behind the partition at one short side of the block of work stations. On the opposite side were windows to a white room with luminance corresponding to an outdoor environment.

On the basis of A-weighted sound pressure level measurements carried out in the test room, equal sound conditions in the eight workstations were confirmed. The measurements also showed the same L_{Aeq} in the first and second hour of the reproduced office noise. Statistical analysis of the recordings showed that high and low noise conditions were similar in respect with time variation, spectra, and speech-to-noise ratio. The percentile analysis showed that the range of sound pressure levels was similar in both noise conditions (see Table 1). That is, statistical distribution of sound pressure levels was similar except that the equivalent levels differed by 12 dB. The Speech Transmission Index (STI) was almost the same in both noise conditions.

2.5. Restoration conditions

After 2 h of work in office noise the participants went through a restoration period for 7 min. There were four different restorative conditions: watching film clips of rivers while listening to corresponding river sounds, listening to the river sounds without the film clips, sitting in silence, or continuing to listen to the office noise from the high noise condition. The nature film contains changing soothing scenes of streaming water and was filmed in different landscapes of the USA (used with permission from Isis Visuals, Ede, The Netherlands; www.natursounds.ca). The river sounds were recorded with a binaural technique to give a better simulation of being in the real sound environment. The river sound is shallow and slow with a birds chirping in the background at a few points. The different film and sound clips were presented to the participants via the computer at their work station.

2.6. Measures

2.6.1. Cognitive performance

We used several different cognitive tasks to measure the effects of the noise and restoration manipulations. Both a cognitive inhibition task and a response inhibition task (further described below) were included to measure fatigue/restoration and were performed three times: in the beginning (pretest), after 1.5 h of work (postwork), and after the restoration period at the end of the experimental sessions (postrest). The other cognitive tasks were included

Table 1
The analysis of two noise conditions in respect with STI and time variation.

		High noise (51 dBA)	Low noise (39 dBA)
Range of STI values		0.00 to 0.66	0.00 to 0.58
Overall variation of SPL, $L_{A,eq,1s}$	dB	40 … 60	31 … 50

only once to measure the effects of the different noise conditions (see Fig. 2 for an overview of the task order). The same order of measures was used for all participants to control the timing between task and noise, since we played back the noise from loudspeakers (and not by headphones for each individual). It would also have been extremely difficult to run this complex experiment with random orders of measures. Since we were not trying to make an evaluation of each specific test, we were ready to take the confounding between tests and time on task.

2.6.1.1. Proactive interference. Proactive interference *(PI)* was measured with a task which taps the ability to inhibit information that once was relevant for recall but has since become irrelevant for the task (Peterson & Peterson, 1959). The participants learned words from ten lists with five words each. The lists were composed of words drawn from the same category. After a list with five words they had to recall the words from the most recent list and ignore (suppress) words from earlier lists. We used the following categories of words: "fruits and vegetables", "animals", "cloths and accessories", "kitchen- and gardening tools", "countries" and "cities in Sweden". The words were presented on the computer screen every 1000 ms and remained for 1000 ms. The orders of the PI-categories within each experimental session were counterbalanced. The following four scores were considered: (1) PI-points: the sum of words recalled from the correct list; (2) PI-pro: the sum of error words (i.e. from earlier lists); (3) PI-no answers: the sum of words not remembered; and (4) PI other errors: the sum of error words (i.e. new words not coming from earlier lists).

2.6.1.2. Response inhibition. Response inhibition was measured with the Sustained Attention to Response Test *(SART)*, which taps the ability to inhibit a physical response and/or sustain attention (Manly et al., 1999). Digits from one to nine were presented repetitively and the participants were told to respond with a key press to all numbers except number three. A digit was presented on the computer screen once every 1000 ms and remained for 1000 ms. Each trial consisted of 100 digits, where 22% were targets (i.e., the number 3) to which the response was to be inhibited. The following scores were considered: (1) the sum of errors of commission (i.e., the number of times the response to the number three was not successfully inhibited); (2) the sum of errors of omission (i.e., the number of times a response was not made to a number which should have been responded to), and; (3) reaction time (i.e., the mean response time in milliseconds for all numbers except number three).

2.6.1.3. Flanker task. We adopted a version of the flanker task (Eriksen & Eriksen, 1974; Heitz & Engle, 2007) as another computerized measure of response inhibition. The participants viewed strings of five letters composed of H and S (e.g. HHHHH, HHSHH). They were told to respond to the central letter by pressing "h" or "s" on the keyboard, inhibiting the other letters (flankers). Before the first letter string was presented in each trial, the symbol "##" was presented and indicated where on the screen the strings were going to be shown. The orienting symbol and the letter strings remained visible for 500 ms. One block consisted of 47 strings, and the mean reaction time for one block was measured.

2.6.1.4. Logical problems. In this task, the participants were presented with logical problems and were told to answer whether the conclusion drawn was true or false (e.g., All A are B. Some B is C. Conclusion: some A is C. Is this conclusion true?). They were told to respond as quickly and correctly as possible. The sum of correct answers was considered.

2.6.1.5. Operation span and reading span. In the operation span test, the participants were presented with sets consisting of a mathematical operation and a word (e.g., Is $(4/2) + 1 = 3$? and then the word "Rose"). The participants were told to respond "yes" or "no" if the mathematical expression was true or not by pressing "Ä" on the keyboard for yes and pressing "A" for no. They were further told to remember the word presented after each mathematical operation. After three to seven tasks they were asked to recall all the words presented. Doing so requires the immediate suppression of the mathematical operations and suppression of words from earlier lists (see Turner & Engle, 1989). The scores were the sum of correct answers in the mathematical operations and the sum of correct words remembered.

The purpose of the reading span task was similar to that of the operation span task. The participants were to decide if a sentence

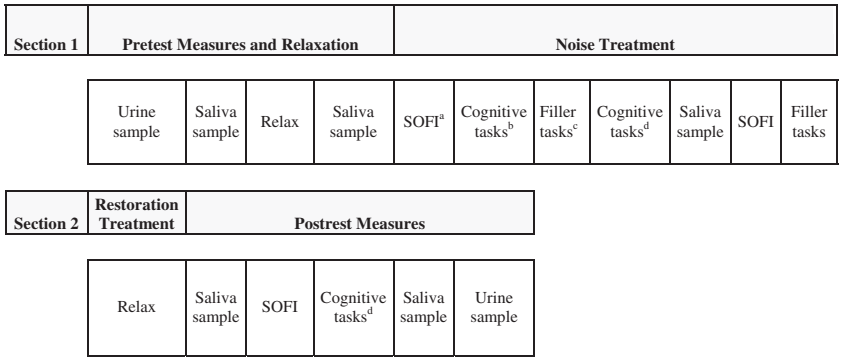


Fig. 2. Overview of the procedure for one experimental session. Section 1 focused on the effects of noise (low and high noise). It was followed immediately by Section 2, which focused on the effects of different options for restoration (Movie of a flowing river with sound, River sound only, Silence, and Noise). [a]Swedish Occupational Fatigue Inventory. [b]The order of the cognitive tasks was as follows: Sustained Attention to Response Test (SART), Proactive interference (PI), Flanker, Reading span, Serial recall – letters, Updating, Operation span, Logical problems, Reading comprehension, Serial recall – numbers, Shifting. It took circa 110 min to complete the tasks. [c]The filler tasks were included to make all participants begin the next phase at the same time. [d] The order of the cognitive tasks at *Postwork* and *Postrest* was as follows: Sustained Attention to Response Test (SART), Proactive interference (PI). It took about 10 min to complete these tasks.

was normal or abnormal and then remember a two-digit number (e.g., "The cloud laugh yellow", Is the sentence normal? and then the number 32). After three to seven tasks they were to recall all the recent numbers presented (see Daneman & Carpenter, 1980).

2.6.1.6. Reading comprehension. This task consists of ten short texts presented sequentially. The texts were adopted from an earlier experiment by Sörqvist et al. (2009). The participants were required to answer one question per text with four alternative answers (only one is correct). The participants had 2 min to answer each question by pressing a button representing their answer (a, b, c, d). If they failed to give an answer within the time limit, the next text was presented. Half of the questions were about the meaning of the text and half of the questions were about a missing word in the text. The score was the sum of correct answers.

2.6.1.7. Serial recall (numbers and letters). In one version of this task, the participants were told to remember a string of seven one-digit numbers and then recall them in the correct order. Each number was presented for 1000 ms and then it was a pause of 600 ms before the next number was presented. Each block consisted of 10 lists and only numbers written at their correct positions were scored as correct. In the other version of this task, they were told to remember a string of seven letters presented in the same way.

2.6.1.8. Shifting. Shifting measures the ability to shift between mental sets. We adopted the number-letter task from Rogers and Monsell (1995), which requires switching between two different categorization operations. The task consists of number-letter pairs (e.g., 3E) presented in a clockwise rotation around all four quadrants on the computer screen. When the number-letter pair is presented in the top two quadrants, the participants are to indicate whether the number is even or odd, and when presented in the bottom two quadrants, they are to indicate whether the letter is a vowel or a consonant. The participants respond by pressing different keys for even/odd and vowel/consonant answers. A number-letter pair is presented on the computer screen every 1000 ms and remains for 1000 ms. Before the participants begin the real task they have three practice trials: (1) to respond to number-letter pairs in the top two quadrants; (2) to respond to number-letter pairs in the bottom two quadrants, and; (3) to respond to the clockwise rotation. The practice trial restarts if a limit of correct answers is not met. The restart limits are 5 (of 8) correct answers in the first two practice trials and 11 (of 16) correct answers in the third trial. The real task score is the sum of correct responses and could reach a maximum of 65 points.

2.6.1.9. Updating. Updating measures the ability to update information in working memory. We used the updating task adapted from Carretti, Cornoldi, and Pelegrina (2007). The task consists of seven lists of 10 two-digit numbers. For each list the participants are instructed to recall the three smallest numbers in the order of presentation. Before the first number, the symbol "##" is displayed to indicate where the numbers are going to be presented. The numbers are presented sequentially in the middle of the computer screen and range from 15 to 99. The arithmetic distance between within-list numbers has been found by Carretti et al. to affect performance. Therefore the highest and the lowest number within a list just vary between 30 and 36 steps in between and two adjacent numbers vary between two and six steps in between. The three smallest numbers recalled and placed in the correct order of each list were scored with one point and the maximum score for one block with seven lists could reach 21 points.

2.6.2. Self ratings of fatigue

Perceived tiredness and motivation were measured with the Swedish Occupational Fatigue Inventory (SOFI) developed by Åhsberg, Gamberale, and Kjellberg (1995). The questions are based on a factor analysis where five components were established for 25 items describing feelings of cognitive- and physical fatigue. Only the three components describing cognitive fatigue were selected for this study. *Lack of energy* was measured with the words "worn out" and "exhausted", *Lack of motivation* with the words "passive" and "uninterested", and *Tiredness* with the words "sleepy" and "the number of yawns for the last 10 min" on a scale ranged from 1 = not at all to 4 = a lot.

2.6.3. Stress hormones

2.6.3.1. Urinary catecholamines. Urine samples were collected directly when all participants had arrived at the laboratory and at the end of the experimental session. For each participant, the exact time after the bladder had been emptied by voluntary voiding was noted, the total urine volume was measured, and 40 ml of urine was mixed in 100 ml glass bottles containing 0.5 ml 2M HCL as a preservative. Samples were stored in a freezer at −20 °C until subsequent preparation. The samples were thawed within 2 months and purified according to the BIO-RAD method (Urinary Catecholamines by HPLC, Reagent Kit, Catalog Number 195-5841/N) and assayed following standard methods for high performance liquid chromatography. The amounts of catecholamines were expressed as ng/h/kg body weight.

2.6.3.2. Salivary cortisol. Saliva samples were obtained with Salivette tubes (Sarstedt, Landskrona, Sweden) at five times during the experimental session (see Fig. 2). It is unclear when exactly to measure a cortisol response, since the peak cortisol response occurs within different time points (Dickerson & Kemeny, 2004) and there might be a time lag before a decline (as after a restoration period) is measurable. The cortisol samples in our study were taken directly when the participants were seated in the simulated office, after 15 min relaxation (before the work session started), after 2 h of work (before the restoration period), after 7 min restoration, and approximately 10 min after the restoration period ended. The radioimmunoassays (RIA) of the samples were carried out in the Stress Research Institute at Stockholm University by a professional blind to the experimental conditions.

2.7. Procedure

Data collection took place at a simulated office at the University of Gävle. Participants went through a practice session for 1 h, several days in advance of the first experimental session. The practice session was meant to reduce possible training effects on the cognitive tasks. To reduce the risk of variations in outcomes according to the weekly calendar (Larsen & Kasimatis, 1990), the experimental sessions only took place on Tuesdays and Thursdays. The experimental sessions were run between 2.00 and 5.00 pm. For each participant, one day separated the two sessions.

The procedure for an experimental session is presented in Fig. 2. The participants started and ended the session with a urine sample and saliva samples were collected at several time points. This enabled checks on the stress hormone levels at the beginning, middle (after 2 h of work), and end of each session.

To reduce possible high levels of stress caused by earlier activities during the day, the participants were given time to relax at their work station in the laboratory office, after the first urine and saliva sample. During this relaxation period they listened (with headphones) to a story about a fictive culture for 15 min. After the relaxation period they provided a second saliva sample and

completed the SOFI. Before they completed the SOFI, the presentation of the office noise was initiated, and the sound level increased gradually to full strength after 1 min. After the SOFI the participants proceeded through the 2 h of cognitive tasks while one of the two different noise conditions (low or high noise) was played back. Filler tasks were included at different time points to assure that all participants always had something to work with and to make it possible to assemble the participants for the next phase of measurements. Performance on these filler tasks was, however, not further analyzed. The session order of the noise conditions was counterbalanced but not the cognitive tasks within the experimental sessions. The cognitive tasks were in the same order in the two experimental sessions since they were to be performed about the same time in the two noise conditions. The session with cognitive tasks started and ended with the PI and SART tests.

After the cognitive work, a saliva sample was taken and the participants again filled out the SOFI. Next, they put their headphones on and went through the 7-min restoration period with one of the four restorative conditions. During the restoration period the background office noise was canceled. For each of the experimental sessions, the participants were randomly assigned to the restorative conditions (i.e., of eight participants at the eight workstations, two watched the movie of the flowing river with sound, two listened only to the sound of the flowing river, two sat in silence, and two listened to office noise delivered through the headphones). The end of the restoration period was indicated by three beeps in the headphones.

After the restoration period the participants took off their headphones and went through the last dependent measures in silence. The whole procedure took about 3 h to complete, and seven to eight participants were tested at each occasion.

2.8. Statistical analyses

SPSS 18.0 was used for statistical analyses. Nine participants were excluded from analysis because of failures to follow task instructions or equipment malfunctioning, leaving 38 participants for further analysis. Data are missing for the first SOFI measure for an additional 14 participants because of problems with the computer script. One additional value is missing in the SOFI measure of tiredness (yawning). Fourteen values for dopamine and one for norepinephrine were lost to analyses because of procedural failures. Since no effects were found on dopamine when the three urine sample measures were analyzed together, we excluded dopamine in a next step of analysis to regain power. A General Linear Model (SPSS version 18) with repeated measures (mixed) design was used for the analysis of noise and fatigue effects. When Mauchly's test indicated non-sphericity in the variance-covariance matrix for the within-subject analyses, the Greenhouse-Geisser adjusted degrees of freedom and corresponding *p*-values are reported for the *F*-tests.

3. Results

Originally a within-person design was intended for the noise manipulation. However, some of the cognitive measures interacted with the sequence of the noise conditions[1]. In general, the interactions were such that performance in the low noise condition was better when this condition was presented first. This might reflect loss of motivation across sessions. The design employed gives an opportunity to safeguard against these order effects by making a between-subjects design of the performance in the first session only. Accordingly, we treated the noise condition in the first session as a between-subjects manipulation.

3.1. Noise effects on cognitive performance

The between-subjects comparison revealed, in accordance with hypothesis 1, a significant main effect of noise on memory for words (PI-points), $F(1, 30) = 4.27$, $p < .05$, *partial* $\eta^2 = 0.13$, indicating a better performance in low noise compared with high noise (see Fig. 3). The analysis did not reveal an effect on the ability to inhibit information (PI-pro), since few participants wrote words from earlier lists ($F < 1$), but it did reveal a significant effect of noise on the number of missing answers (PI-no answers), $F(1, 30) = 6.62$, $p < .05$, *partial* $\eta^2 = 0.18$. The participants had more no answers (i.e. words not remembered) in high noise compared to low noise. There were, however, no statistically significant effects of noise on the other cognitive measures (all $Fs < 1$).

3.2. Noise effects on acute psychophysiological stress

There were no interactions between noise and session order for the physiological measures. Consequently, noise was treated as a within-subjects factor.

The analysis revealed an effect of time on the cortisol levels $F(1.16, 34.91) = 31.12$, $p < .001$, *partial* $\eta^2 = 0.51$ (see Fig. 4). The participants showed high levels of cortisol when they arrived to the experimental session, and the level had declined in both noise conditions after 2 h of work. There was no statistically significant effect of noise on the decline in the level of cortisol ($F < 1$). We thus did not find support for hypothesis 2.

A significant effect of time was also shown on the norepinephrine levels from the urine samples, $F(1, 35) = 30.40$, $p < 0.001$, *partial* $\eta^2 = 0.47$, with a decline from Pretest to Postrest in both noise conditions (see Fig. 5). There were no statistically significant effects of noise on the level of catecholamines ($F < 1$).

3.3. Noise effects on self ratings of fatigue

For the subjective ratings (SOFI-measures), we found no interactions between noise and session order, and were therefore free to analyze the within-subjects effects of noise. Both noise and time

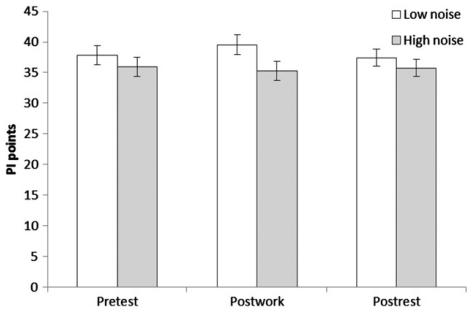


Fig. 3. The number of words remembered at *Pretest, Postwork, and Postrest*in low noise ($n = 18$) and high noise ($n = 20$). Error bars are the standard errors of the mean.

[1] The cognitive measures which showed a significant interaction ($p < 0.05$) with the sequence of the noise conditions presented first: PI-points, $F(1, 36) = 4.49$, partial $\eta^2 = 0.11$; PI-no answers, $F(1, 36) = 6.40$, partial $\eta^2 = 0.15$; Flanker-reaction time, $F(1, 30) = 11.82$, partial $\eta^2 = 0.28$; Logical problems-points, $F(1, 30) = 14.53$, partial $\eta^2 = 0.33$; Serial recall-letter points, $F(1, 30) = 11.04$, partial $\eta^2 = 0.27$; Serial recall-number points, $F(1, 30) = 9.06$, partial $\eta^2 = 0.23$.

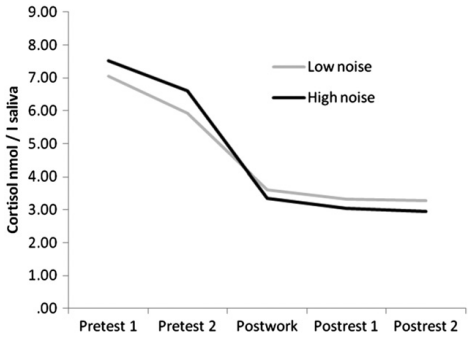


Fig. 4. Cortisol levels (nmol/l saliva) in low- and high noise ($n = 38$) at *Pretest, Postwork, and Postrest.* Note: *Pretest1* = at arriving, *Pretest 2* = after relaxation; *Postrest 1* = after seven minutes of restoration, *Postrest 2* = after additional 5–10 minutes.

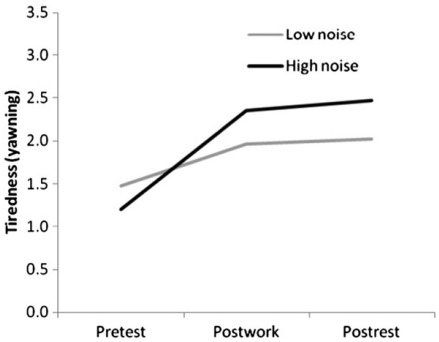


Fig. 6. Self ratings of tiredness (yawning) the last 10 minutes in low- and high noise ($n = 23$) at *Pretest, Postwork, and Postrest.* Note: The scale ranged from 1 = not at all to 4 = a lot.

effects were of interest. In this section we focus on the measures from Pretest (at arrival) to Postwork (after 2 h of work).

The analysis revealed a significant interaction between noise and time on tiredness (yawning), $F(2, 32) = 6.25$, $p < 0.01$, *partial* $\eta^2 = 0.28$; and on lack of motivation (passiveness) $F(2, 32) = 4.33$, $p < 0.05$, *partial* $\eta^2 = 0.21$. In line with hypothesis 3, the participants rated themselves as more tired and less motivated after 2 h of work in high noise compared to low noise (see Figs. 6 and 7, Pretest and Postwork).

3.4. Restoration

When comparing the SOFI scores from Postwork (before the restoration period) to Postrest (after restoration), the analysis revealed a significant between-subjects effect of restorative conditions on change in the ratings of lack of energy (exhaustion), $F(3, 29) = 3.10$, $p < 0.05$, *partial* $\eta^2 = 0.24$; and of lack of motivation (uninterested) $F(3, 29) = 3.02$, $p < 0.05$, *partial* $\eta^2 = 0.24$. Decomposition of this effect using simple effects analysis (LSD) demonstrated that the participants who saw the movie (including river sounds) rated themselves as *having more energy* (i.e., were less exhausted) in comparison with the participants listening to noise ($p < 0.01$) and those listening to river sounds ($p < 0.05$). The participants who listened to noise during the restoration period rated themselves as being *less motivated* (i.e., more uninterested) in comparison with the participants who listened to river sounds ($p < 0.05$) or saw the movie ($p < 0.01$), see Figs. 8 and 9. The post hoc analysis also demonstrated a marginal difference in *tiredness* (yawning) between the movie condition and the noise condition ($p = 0.055$) and between the movie and river sound conditions ($p = 0.052$). An inspection of Table 2 indicates that the participants who heard river sounds or office noise during the restoration period rated their overall experience more negatively than the participants in the other two restoration conditions.

No statistically significant effects from the restoration period were detected on the cognitive or physiological measures.

4. Discussion

In this experimental study we approached two main issues concerning open-plan offices. First, we examined the effects of two levels of office noise on basic working memory processes, self-ratings of mood and fatigue, and physiological measures of stress (salivary cortisol and urinary catecholamines) in a simulated open-plan office. Second, we examined the effects of varying sound conditions on restoration during short period after 2 h of work.

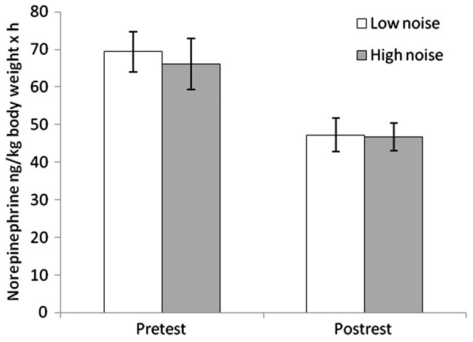


Fig. 5. Norepinephrine levels (ng/kg body weight × height) in low- and high noise ($n = 37$) at *Pretest and Postrest.*

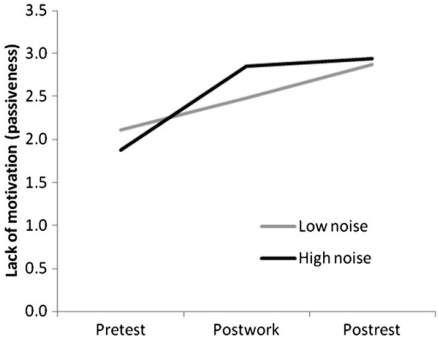


Fig. 7. Self ratings of low motivation (passiveness) in low- and high noise ($n = 24$) at *Pretest, Postwork, and Postrest.* Note: The scale ranged from 1 = not at all to 4 = a lot.

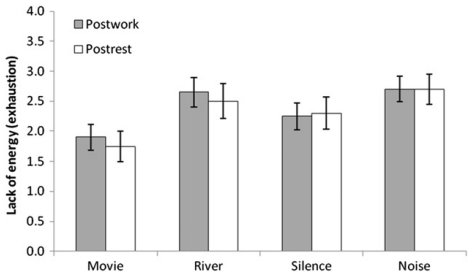


Fig. 8. Self-ratings of lack of energy (exhaustion) before and after 7 minutes of rest in each restorative condition (movie, $n = 10$; river, $n = 8$; silence $n = 9$; and noise, $n = 10$). Error bars are the standard errors of the mean for group comparisons. Note: The scale ranged from 1 = not at all to 4 = a lot.

4.1. Effects of noise on cognitive performance

We employed different cognitive tasks with focus on the ones which have been developed to tap three basic cognitive functions (inhibition, updating and shifting), to see whether some or all of these functions were affected by office noise. We also included other tasks which have been used in earlier studies of office noise such as reading comprehension, serial recall and operation span.

In accordance with Hypothesis 1, there was a main effect of noise on memory for words (PI-points), indicating that performance declined more in high noise compared to low noise. However, no effects were shown on the number of proactive interferences (inhibition), since few participants wrote words from earlier lists. We had not included in the instruction that they always should write five words even when they were not sure or could not remember. There was instead a significant effect of noise on the number of missing answers. However, the number of words the participants did or did not remember cannot tell which specific cognitive processes were involved and therefore affected by noise.

Further, it was unexpected that no other noise effects would be revealed on the additional cognitive measures. This might be explained by limitations of the present study. First, Hongisto (2005) has suggested that it is not the noise level of office noise that affects cognitive performance but the intelligibility of speech, or STI if we want to put it into a physical measure. The STI of the low noise condition did not differ much from the high noise condition although the overall noise level was reduced by 12 dB (Table 1). According to Hongisto, the cognitive performance improves only if STI reduces from highly intelligible speech (STI at least 0.60) to poorly intelligible speech (STI less than 0.30). This may be one of

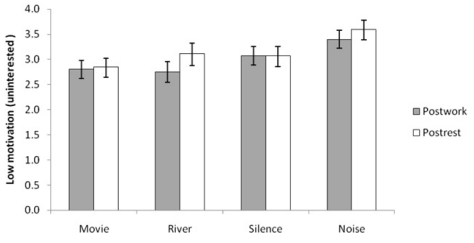


Fig. 9. Self-ratings of low motivation (uninterested) before and after 7 minutes of rest in each restorative condition (movie, $n = 10$; river, $n = 8$; silence $n = 9$; and noise, $n = 10$). Error bars are the standard errors of the mean for group comparisons. Note: The scale ranged from 1 = not at all to 4 = a lot.

Table 2
The mean change in the SOFI-measures in different restorative conditions. Negative values indicate decrease from before to after the rest period (i.e. improvement).

	Movie	River	Silence	Noise
Sleepy	−.40	.00	−.44	−.45
Exhaustion	−.20	−.13	.11	.18
Passive	.00	−.25	.11	.27
Yawning	.10	.25	−.56	−.18
Worn out	−.10	.25	−.11	.00
Uninterested	.30	.25	−.22	.27
Mean	−.05	.06	−.19	.02

Note: The scales ranged from 1 = not at all to 4 = a lot.

the reasons why some of the cognitive measures were independent of our noise manipulation. Second, the exposure times can be critical for performance effects to appear, since research has shown that it is possible to compensate for adverse sound conditions during shorter exposures by exerting extra effort (Kjellberg, 1997). The participants also knew the duration of the session which might have mitigated their tolerance of the noise exposure. In the long run, however, consequences like fatigue and less efficiency might emerge and affect performance. This could have been the case if the exposure time in this study had been longer than 2 h, since the subjective ratings indicated fatigue effects. Interesting results of this study is that noise level and absorption proved to be of importance for memory performance. These results, however, are different from some earlier findings. Ellermeier and Hellbrück (1998) found for example no effects of office noise level (75 dBA and 60 dBA overall level) on cognitive performance. Further research is needed to further explore the relation between cognitive performance and varying acoustic conditions (level, STI, fluctuation etc.) in order to find a good balance for performance in open-plan offices.

4.2. Effects of noise on acute stress effects

The participants showed a significant decline in cortisol in both noise conditions over time, consistent with the decline that occurs as a part of normal circadian variation. The same pattern is shown in norepinephrine measured from urine. The results thus give no support for Hypothesis 2. Further studies need to address the question on how to deal with high stress levels from start. According to this study 15 min relaxation in the beginning was not enough.

4.3. Effects of noise on self ratings of fatigue

In line with Hypothesis 3, the participants felt more tired and less motivated after they had worked for 2 h in high noise compared to low noise. This is in line with other studies indicating motivational deficits, irritability and fatigue among groups exposed to noise (reviewed by Kjellberg, 1997).

Chigot (2005) has in a review indicated that subjective experience seldom paralleled the objective assessment of the effects of noise in offices, and this seems to have been the case also in this study. Further research should therefore continue to explore the effects of noise with different measures.

4.4. Restoration

After 2 h of work the participants had 7 min to restore. The participants who saw a movie of a flowing river with corresponding sound reported having more energy compared to the participants who just listened to river sounds, or those who continued to listen to office noise. The participants who listened to office noise during

the restoration phase also experienced themselves to be less motivated after this period, compared to the participants who listened to river sounds, and those who saw the nature movie with river sounds. These results support Hypothesis 4 by indicating that the sound conditions may promote different restorative experiences. There were, however, no significant effects of restoration condition on the cognitive or physiological measures, which might be due to the small sample for comparison in each restorative condition and/or the brief period allowed for restoration. Increasing the restorative period would be a good starting point for clarifying within which timespan different effects start to emerge (cf. Hartig et al., 2003). However, the timespan needed probably depends on the antecedent condition of fatigue and the environmental conditions investigated.

To sum up, further research needs to address the issues of which cognitive processes get fatigued with noise, how long a restorative phase is needed to get the specified processes restored, and which environmental sounds promote restoration.

4.5. Conclusion and practical implications

The design of work environments has significance for employee wellbeing and performance. In this study the results showed that the participants' memory performance declined more in high noise compared to low noise, and that they experienced more tiredness and less motivation with high noise. Significant reduction of noise level can reduce the negative effects of background noise in open-plan offices. This study included a reduction of noise level by 12 dB which is very challenging to reach in office environments. It requires simultaneous consideration of many noise control measures (Virjonen, Keränen, & Hongisto, 2009) and silent behavior in the office (office etiquette).

We saw no reliable noise effects on the physiological measures. This finding suggests that the effects of short-term noise exposure on cognitive performance are not mediated by a change in physiology. In real-life long-term chronic noise exposure this may be different but to what extent we cannot say from the present study.

Further research is needed to find the best combination of reduced noise level, speech intelligibility and intermittent sounds to enhance performance and well-being in open-plan offices. There should also be further concern for designing sound environments that can promote daily restoration at workplaces. Rest in office noise affected motivation in a negative way. This study also indicated that a movie of a flowing river with corresponding water sound is experienced as giving more energy than staying in continued office noise or just listening to river sounds for 7 min.

So far, many environments have just been studied according to their visual value for restoration. Therefore, multi-modal restoration also needs to be addressed in a larger context than at work. Looking at a combination of senses might indicate that a nature environment such as a noisy park might restrict restoration while a quiet park environment, where only nature sounds are heard, might promote restoration. When comparing different environments, it might also turn out that a calm café with soft music in a noisy urban environment might be more restorative than going to a crowded and noisy park, which would contrast with earlier results. The noise level increments at workplaces and in urban areas demand compensatory strategies that include access to restorative environments. These are health issues that need to be further addressed.

Acknowledgments

This research was funded by AFA Insurance and by the University of Gävle and was conducted in partial fulfilment of the requirements for a doctoral degree. We would like to thank Dr. Örjan Johansson and Dr. Johan Odelius at Luleå University of Technology for their help with the recording and arrangement of the office noise used in this experiment; Dr. Valtteri Hongisto and David Oliva for their help with analysing the STI of speech in the office noise recordings; and Professor Terry Hartig for helpful advice in planning and conducting this study and for comments on earlier drafts of this paper. We are also thankful to Dr. Patrik Sörqvist at the University of Gävle for advice concerning the cognitive tasks; Lars Holmberg at the Stress Research Institute, Stockholm University for help with analyzing the saliva samples; Ecophon and S-line office for their donation to the office setting; and anonymous reviewers for their helpful comments.

References

Åhsberg, E., Gamberale, F., & Kjellberg, A. (1995). *Upplevd trötthetskvalitet vid olika arbetsuppgifter. Utveckling av ett mätinstrument.* [*Perceived fatigue quality during different work tasks. Development of a measure*]. Solna: Arbetsmiljöinstitutet. nr. 20.

Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4*, 417–423.

Baddeley, A. D. (2002). Is working memory still working? *European Psychologist, 7*, 85–97.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. A. Bower (Ed.), *The Psychology of learning and motivation* (pp. 47–89). New York, N.Y: Academic Press.

Banbury, S., & Berry, D. C. (1998). Disruption of office-related tasks by speech and office noise. *British Journal of Psychology, 89*, 499–517.

Banbury, S. P., Macken, W. J., Tremblay, S., & Jones, D. M. (2001). Auditory distraction and short-term memory: Phenomena and practical implications. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 43*, 12–29.

Berman, M. G., Jonides, J., & Kaplan, S. (2008). The cognitive benefits of interacting with nature. *Psychological Science, 19*, 1207–1212.

Berto, R. (2005). Exposure to restorative environments helps restore attentional capacity. *Journal of Environmental Psychology, 25*, 249–259.

Carretti, B., Cornoldi, C., & Pelegrina, S. L. (2007). Which factors influence number updating in working memory? The effects of size distance and suppression. *The British Psychological Society, 98*, 45–60.

Chigot, P. (2005). Effects of sound in offices: subjective experience vs. objective assessment. *Facilities, 23*, 152–163.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19*, 450–466.

De Croon, E. M., Sluiter, J. K., Kuijer, P. P., & Frings-Dresen, M. H. W. (2005). The effect of office concepts on worker health and performance: A systematic review of the literature. *Ergonomics, 48*, 119–134.

Dickerson, S. S., & Kemeny, M. E. (2004). Acute stressors and cortisol responses: A theoretical integration and synthesis of laboratory research. *Psychological Bulletin, 130*, 355–391.

Ellermeier, W., & Hellbrück, J. (1998). Is level irrelevant in "irrelevant speech"? Effects of loudness, signal-to-noise ratio, and binaural unmasking. *Journal of Experimental Psychology, 24*, 1406–1414.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16*, 143–149.

Evans, G. W., & Johnson, D. (2000). Stress and open-office noise. *Journal of Applied Psychology, 85*, 779–783.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology, 133*, 101–135.

Haka, M., Haapakangas, A., Keränen, J., Hakala, J., Keskinen, E., & Hongisto, V. (2009). Performance effects and subjective disturbance of speech in acoustically different office types – A laboratory experiment. *Indoor Air, 19*, 454–467.

Hartig, T., Böök, A., Garvill, J., Olsson, T., & Gärling, T. (1996). Environmental influences on psychological restoration. *Scandinavian Journal of Psychology, 37*, 378–393.

Hartig, T., Evans, G. W., Jamner, L. D., Davis, D. S., & Gärling, T. (2003). Tracking restoration in natural and urban field settings. *Journal of Environmental Psychology, 23*, 109–123.

Hartig, T., Mang, M., & Evans, G. W. (1991). Restorative effects of natural environment experiences. *Environment and Behavior, 23*, 3–26.

Hedge, A. (1982). The open-plan office: A systematic investigation of employee reactions to their work environment. *Environment and Behavior, 14*, 519–542.

Heitz, R. P., & Engle, R. W. (2007). Focusing the spotlight: Individual differences in visual attention control. *Journal of Experimental Psychology, 136*, 217–240.

Hongisto, V. (2005). A model predicting the effect of speech of varying intelligibility on work performance. *Indoor air, 15*, 458–468.

Jones, D. (1990). Recent advances in the study of human performance in noise. *Environment International, 16*, 447–458.

Jones, D., & Morris, N. (1992). Irrelevant speech and serial recall: Implications for theories of attention and working memory. *Scandinavian Journal of Psychology, 33*, 212–229.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99*, 122–149.
Khalfa, S., Bella, S. D., Roy, M., Peretz, I., & Lupien, S. J. (2003). Effects of relaxing music on salivary cortisol level after psychological stress. *Annals New York Academy of Science, 999*, 374–376.
Kjellberg, A. (1997). Noise. In H. A. Waldron, & C. Edling (Eds.), *Occupational health practice* (4th edition). (pp. 241–256). Oxford: Butterworth Heinemann.
Kjellberg, A., & Sköldström, B. (1991). Noise annoyance during the performance of different nonauditory tasks. *Perceptual and Motor Skills, 73*, 39–49.
Kristiansen, J., Mathiesen, L., Nielsen, P. K., Hansen, A. M., Shibuya, H., Petersen, H. M., et al. (2008). Stress reactions to cognitively demanding tasks and open-plan office noise. *International Archives of Occupational and Environmental Health, 82*, 631–641.
Larsen, R. J., & Kasimatis, M. (1990). Individual differences in entrainment of mood to the weekly calendar. *Journal of Personality and Social Psychology, 58*, 164–171.
Laumann, K., Gärling, T., & Stormark, K. M. (2001). Rating scale measures of restorative components of environments. *Journal of Environmental Psychology, 21*, 31–44.
Laumann, K., Gärling, T., & Stormark, K. M. (2003). Selective attention and heart rate responses to natural and urban environments. *Journal of Environmental Psychology, 23*, 125–134.
Lustig, C., May, C. P., & Hasher, L. (2001). Working memory span and the role of proactive interference. *Journal of Experimental Psychology, 103*, 199–207.
Manly, T., Robertson, I. H., Galloway, M., & Hawkins, K. (1999). The absent mind: further investigations of sustained attention to response. *Neuropsychologia, 37*, 661–670.
Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49–100.
Navai, M., & Veitch, J. A. (2003). *Acoustic satisfaction in open-plan offices: Review and recommendations (IRC-RR-151)*. National research council Canada: Institute for Research in Construction.
Oommen, V. G. O., Knowles, M. K., & Zhao, I. Z. (2008). Should health service managers embrace open plan work environments? A review. *Asia Pacific Journal of Health Management, 3*, 37–43.
Peterson, L., & Peterson, M. J. (1959). Short-term retention of individual verbal items. *Journal of Experimental Psychology, 58*, 193–198.
Rashid, M., & Zimring, C. (2008). A review of the empirical literature on the relationships between indoor environment and stress in health care and office settings: Problems and prospects of sharing evidence. *Environment and Behavior, 40*, 151–190.
Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology, 124*, 207–231.
Roper, K. O., & Juneja, P. (2008). Distractions in the workplace revisited. *Journal of Facilities Management, 6*, 91–109.
Schlittmeier, S., Hellbrück, J., Thaden, R., & Vorländer, M. (2008). The impact of background speech varying in intelligibility: Effects on cognitive performance and perceived disturbance. *Ergonomics, 51*, 719–736.
Sloan, R. P. (1991). Cardiovascular effects of noise. In T. H. Fay (Ed.), *Noise and health* (pp. 15–26). New York: The New York Academy of Medicine.
Smith-Jackson, T. L., & Klein, K. W. (2009). Open-plan offices: Task performance and mental workload. *Journal of Environmental Psychology, 29*, 279–289.
Sörqvist, P., Halin, N., & Hygge, S. (2009). Individual differences in susceptibility to the effects of speech on reading comprehension. *Applied Cognitive Psychology, 24*, 67–76.
Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory & Language, 28*, 127–154.
Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology, 11*, 201–230.
Venetjoki, N., Kaarlela-Tuomaala, A., Keskinen, E., & Hongisto, V. (2006). The effect of speech and speech intelligibility on task performance. *Ergonomics, 49*, 1068–1091.
Virjonen, P., Keränen, J., & Hongisto, V. (2009). Determination of acoustical conditions in open-plan offices – Proposal for new measurement method and target values. *Acta Acustica united with Acustica, 95*, 279–290.
Waye, K. P., Bengtsson, J., Rylander, R., Hucklebridge, F., Evans, P., & Clow, A. (2002). Low frequency noise enhances cortisol among noise sensitive subjects during work performance. *Life Sciences, 70*, 745–758.

Paper II

Pre-print copy *Noise & Health* (2012), *14*

Performance, fatigue and stress in open-plan offices: The effects of noise and restoration on hearing impaired and normal hearing individuals

Helena Jahncke, Niklas Halin

Department of Environmental Psychology, Faculty of Engineering and Sustainable Development, University of Gävle, SE-801 76 Gävle, Sweden

Abstract

Hearing impaired and normal hearing individuals were compared in two within-participant office noise conditions (*high noise*: 60 L_{Aeq} and *low noise*: 30 L_{Aeq}). Performance, subjective fatigue, and physiological stress were tested during working on a simulated open-plan office. We also tested two between-participants restoration conditions following the work period with high noise (nature movie or continued office noise). Participants with a hearing impairment (N = 20) were matched with normal hearing participants (N = 18) and undertook one practice session and two counterbalanced experimental sessions. In each experimental session they worked for two hours with basic memory and attention tasks. We also measured physiological stress indicators (cortisol and catecholamines) and self-reports of mood and fatigue. The hearing impaired participants were more affected by high noise than the normal hearing participants, as shown by impaired performance for tasks that involve recall of semantic information. The hearing impaired participants were also more fatigued by high noise exposure than participants with normal hearing, and they tended to have higher stress hormone levels during the high noise compared to the low noise condition. Restoration with a movie increased performance and motivation for the normal hearing participants, while rest with continued noise did not. For the hearing impaired participants, continued noise during rest increased motivation and performance, while the movie did not. In summary, the impact of noise and restorative conditions varied with the hearing characteristics of the participants. The small sample size does however encourage caution when interpreting the results.

Keywords: Hearing status, Memory, Motivation, Open plan office, Physiology

Introduction

There are concerns about the effects of noise on cognitive performance and health in open-plan offices (see reviews).[1-3] These concerns are strengthened by experimental studies which indicate that noise (such as irrelevant speech) impairs performance[4-6] and increases stress.[7] In a previous study from our laboratory we also found effects of realistic office noise on cognitive performance.[8]

There are good reasons to expect that the impacts of noise in an open-plan office vary not only with the types of noise and the layout of the office, but also with the characteristics of the individuals exposed to noise. One important individual difference variable is hearing status. In Sweden more than 10% of the population have some hearing impairment and among those more than half are of working age.[9] No studies to our knowledge have systematically addressed how individuals with a hearing impairment fare (physiologically and psychologically) in open-plan offices. For example, it appears that no research has considered whether hearing impaired individuals' work performance is disrupted by background speech or how stressful they experience a noisy background to be.

If noise has a negative effect on office workers, one important strategy is to find ways to attenuate the negative outcomes. Jahncke *et al*.[8] showed that a 7 minute break from work in office noise promotes restorative experiences in university students with normal hearing. Restorative effects are typically seen after a break as less fatigue, reduced psychophysiological activity (e.g. blood pressure, stress hormones) and/or increased cognitive/attentional performance.

The aim of the present study was to investigate whether

Access this article online	
Quick Response Code:	Website: www.noiseandhealth.org
	DOI: ***
	PubMed ID: ***

open-plan office noise affects performance and stress, and whether these effects differ between hearing impaired and normal hearing individuals. In addition we investigated the restorative effects of 14 minutes break with two different restorative conditions.

Hearing impairment and performance in Noise

Most studies concerning individuals with hearing impairment have focused on performance and listening effort in tasks involving speech processing. The results show that background noise has a larger effect for the hearing impaired than for normal hearing individuals in these tasks (for a review, see.[10]) Furthermore, both subjective and objective measures indicate that background noise forces the hearing impaired to exert more effort in speech recognition tasks than is necessary for individuals with normal hearing.[11,12] To the extent that the task involves speech perception (e.g. taking a phone call), background noise thus is therefore likely to be more detrimental for the hearing impaired than for individuals with normal hearing.

It is not apparent whether this stronger effect from background noise for the hearing impaired also applies to non-auditory tasks. By itself, a hearing loss may be favorable when performing visual tasks in office noise, as the noise is not as prominent or intelligible for the hearing impaired as it is for individuals with normal hearing. On the other hand, most individuals with a serious hearing impairment use a hearing aid, which may amplify the sound to a normal hearing level. However, the hearing aid may also distort the speech signal,[13] which may lead to more distraction for the hearing impaired. Recruitment, which refers to the finding that the same increase in signal strength gives a larger increase in perceived loudness in a non-normal ear than in the normal ear[14] may also play a part here by leading to the perception of sharp onsets of sound that capture attention away from focal task processing much like an auditory deviant.[15] Therefore, for the hearing impaired, as compared to the normal hearing individuals, there may be an additional demand of resisting attentional capture which may cause disruption of or less efficient, focal task processing. In the present study we included noise with temporal variations of speech, phones ringing, and office clatter etc. from working life (i.e. a recording from an actual open-plan office) to test whether the hearing impaired individuals are more distracted in a situation with louder noise than are individuals with normal hearing.

Hearing impairment, fatigue and stress

Babisch[16] reviewed findings concerning stress hormones in relation to research on the cardiovascular effects of noise. Interestingly there are some studies showing specific effects of noise on stress that are related to hearing and noise sensitivity. For example, Melamed and Bruhis[17] performed a field study on industrial workers and have shown that the workers had increased urinary cortisol levels after a day without wearing hearing protection compared with when using them (i.e. a difference of 30-33 dB).

Persson-Waye *et al*.[18] have also showed that after two hours of cognitive work in low-frequency noise (i.e., ventilation noise), normal hearing individuals that reported themselves as highly sensitive to noise maintain higher cortisol levels than individuals that report less sensitivity to noise. Therefore, higher cortisol levels could be expected in individuals who are highly sensitive to sounds because of a hearing impairment. However, to the authors' knowledge no studies have been reported that demonstrate such a relationship.

Restoration

The study of restoration in different contexts has been guided by different theoretical approaches that entail different outcomes over time.[19-21] There are lack of studies that investigate low-cost ways to provide well-being and efficiency at work.[22] One way to promote restoration has been to use film-clips or pictures of nature[23,24] that can easily be used during a break in an office environment.[8] For a review of the psychological benefits of nature experiences see Bowler *et al*.[25] However, from reported research on restorative environments, it cannot be well specified how long the restorative period should be to improve performance and how varying sound conditions might influence the effectiveness of the restorative period. We attempted to address this in the present study. In a previous study Jahncke *et al*.[8] tested two cognitive tasks in an attempt to tap fatigue effects: the response inhibition task (SART) and a cognitive inhibition task (Proactive interference), but failed to show any effects of a seven minute rest on task performance. The authors argued that this may be due to ceiling effects. In the present study we attempt to make the response inhibition task more difficult. We also include another task, mental arithmetic, which has been shown to be cognitively fatiguing to perform.[26] Performance on this task may therefore be more sensitive to the benefits of a restorative break. In addition, we double the rest period to 14 minutes.

Hypotheses

Our hypotheses are

Hypothesis 1: Within each of the two hearing groups, there will be an effect of noise on (a) *cognitive processing* resulting in depreciation in cognitive performance with high noise, (b) *stress hormones* resulting an increase in hormones associated with stress in the context of high noise, and (c) *self ratings* of sleepiness and lack of motivation, whereby sleepiness and lack of motivation will increase with work in the high noise compared to the low noise condition.

Hypothesis 2: There will be an interaction between noise and hearing level on the dependent measures. The hearing impaired individuals are expected to have more difficulties (i.e. task performance will be reduced, stress hormone levels will increase and they will be more fatigued) in high noise

compared to normal hearing individuals because they are possibly more sensitive and distracted by high sounds. In low noise however, normal hearing individuals may have more difficulties than the hearing impaired because the noise might be more prominent for them at this level.

Hypothesis 3: Participants will restore from fatigue (measured as performance on cognitive tasks, self-ratings and cortisol levels) to differing degrees as a function of restoration conditions. More precisely, we expect a nature movie without sound (positive stimuli) to be more restorative than noise (negative stimuli).

Methods

Design

We used a 2 × 2 mixed factorial experiments, with one between-participants factor (hearing level) and one within-participant factor (noise condition). We also had two different between-participants restorative conditions at the end of the high noise sessions. The participants either watched a nature movie with no sound or listened to office noise without a movie (between-participants manipulations). During the low noise session all participants sat in quiet during the restorative period, to assure the same session length in both noise conditions.

Participants

The participants in the study were 20 hearing impaired (nine females; median age = 53) and 18 normal hearing individuals (eight females; median age = 48). The participants with hearing impairment were recruited from the Swedish association of the Hard of Hearing Persons (HRF) and we only included those in the age span 20-65 years old. Those who reported having severe tinnitus and/or Menières disease were excluded. In the next step we recruited matched normal hearing participants following the criteria of the same gender, age (accepted with small age variation), occupation and education as the hearing impaired individuals. Out of the 38 participants, 20 had earlier worked with office tasks, and 10 had some experience with open-plan offices. Participants' hearing abilities were screened [see Figures 1A and B for the means of the audiograms for the hearing impaired and normal hearing group]. The standard deviation across all values was 24.83 for the hearing impaired and 5.28 for the normal hearing participants. The criterion to be included in the hearing impaired group was a mean hearing loss of 28 dB or more over the frequencies 500, 1000, 2000 and 4000 Hz, which did not give any overlap between the two groups. The participants with hearing-aids were told to have them turned on during the experiments. Participants were informed of the nature of the study before participating and they were randomly assigned to the two sequence orders of the two noise conditions. Participation in all sessions of the experiment was compensated with 990 Swedish crowns.

Research setting

The research was carried out in an office laboratory (63 m^2) at the University of Gävle. The room was designed to simulate a neutral open-plan office including windows to a white room with simulated outdoor lighting. Ambient conditions in the indoor environment were kept approximately constant throughout the experiments. The room temperature at the work place varies in-between 20.7-21.6°C during the experimental sessions. The airflow was 20 l/s for each person in the experiment, and the CO^2 concentration was always well below 1000 ppm. Luminance was set to 480-520 lx incident on the height of the seating in each workstation and met the current recommendations in Sweden for work with computers.[27] The luminance in the room outside the window was set to 1950 lx measured at the middle of the window.

The workstations were separated by 1.43 m high screens. Each cubicle was 1.24 m wide. At each end of the set of cubicles a pane of glass was installed to better avoid direct sounds from the loudspeakers to the participants sitting close by. Behind the participants on each side were also 3.60 m wide × 1.80 m high screens to better avoid direct sounds from the loudspeakers behind.

Noise conditions

We recorded the noise used in the experiment in an actual open-plan office in Sweden. From the multi-channel recording, one hour of office noise was extracted, edited and reproduced in the test room with eight loudspeakers, two at each wall, and one subwoofer. In the high noise condition, additional phone and sound signals were added to the office noise. The phone signals consisted of different mobile tunes and stationary telephones ringing. The speech signals were conversations recorded from radio, from which we cut away one of the voices to simulate telephone conversations. The high noise was reproduced with an equivalent A-weighted sound level of 60 L_{Aeq} in the room. In the low noise condition the added phone and sound signals were excluded and the noise was low pass filtered, which reduced L_{Aeq} in the room by 12 dBA. The sound level was further attenuated to reach 30 L_{Aeq}. The one hour office noise tape was looped once, and the sound signals in the latter hour were rotated 180 degrees to equalize noise exposure throughout the room.

The sound level measurements showed the same L_{Aeq} in the first and second hour of the reproduced office noise. The statistical distribution of sound pressure levels was similar in the high and low noise conditions except that the equivalent levels differed by 30 dB. The Speech Transmission Index (STI) was the same for the high noise condition (60 dB) in this study, as for the high noise condition (51 dB) in the earlier study by Jahncke *et al*.[8] The STI values in the low noise condition (30 dBA) were lower than in the low noise condition (39 dB) by Jahncke and colleagues. The speech noise in the low noise condition was

now so close to the hearing threshold that it was not possible to hear the weakest speech sounds.

Restoration conditions

After two hours of work in office noise the participants went through a restoration period for 14 minutes. Two different restorative conditions were tested after the high noise condition: half of the participants saw a movie with clips of nature environments in quiet and half of the participants were exposed to continued office noise. In the low noise condition, all participants sat in quiet during the restorative period. In the analysis of restoration effects only the movie and office noise conditions were compared, as the quiet condition differed from these to conditions also with respect to the preceding noise condition.

Measures

Cognitive performance

We used several different cognitive tasks to measure the effects of the noise and restoration manipulations. A response inhibition- and an arithmetic test (further described below) were included to measure fatigue/restoration and were performed three times: in the beginning (pretest), after 2 hours of work (Post work), and after the restoration period at the end of the experimental sessions (Post rest). The other cognitive tasks were included twice to measure change across time in noise, except for the reading comprehension task that was included once per session because of the time it took to perform [see Figure 2 for an overview of the task order]. The same presentation order of dependent measures was used for all participants to control for the timing between task and noise. As we were not trying to make an evaluation of each specific test, we were ready to take the confounding between when and which task was performed in return for a reduced error term.

Response inhibition

Response inhibition was measured with the Sustained Attention to Response Test (*SART*), which taps the ability to inhibit a physical response and/or sustain attention.[28] Digits from one to nine were presented repetitively and the participants were told to respond with a key press to all numbers except three target numbers (i.e., 2, 5 and 9). A digit was presented on the computer screen once every 1000 ms and remained for 1000 ms. Each trial consisted of 140 digits where 15% were targets (i.e., number 2, 5, 9) to which the response was to be inhibited. The following scores were considered: (1) the sum of errors of commission (i.e., the number of times the response to the targets was not successfully inhibited); (2) the sum of errors of omission (i.e., the number of times a response was not made to a number which should have been responded to), and (3) reaction time (i.e., the mean response time in milliseconds for all numbers except the target numbers).

Arithmetic's

This task was a computational task with ten single-digit numbers, which were presented one by one on the screen. The operation to perform (+ or -) was presented between the numbers. The participants controlled the presentation speed. When all the ten numbers were presented the participants typed in the answer.[29] In total there were 16 sets and the scores were the sum of correct answers and the time it took to complete the arithmetic task.

Math

This was a simple addition task whereby participants were required to add double-digit (e.g. easy task; 44+38) and triple-digit numbers (e.g. difficult task; 122+435). Each experimental block consisted of 15 double-digit and 15 triple-digit expressions. The answer time was set at 20 seconds for each math expression. The task always started with a difficult expression that was followed by an easy expression and so on. The scores were the sum of correct answers (divided in the easy

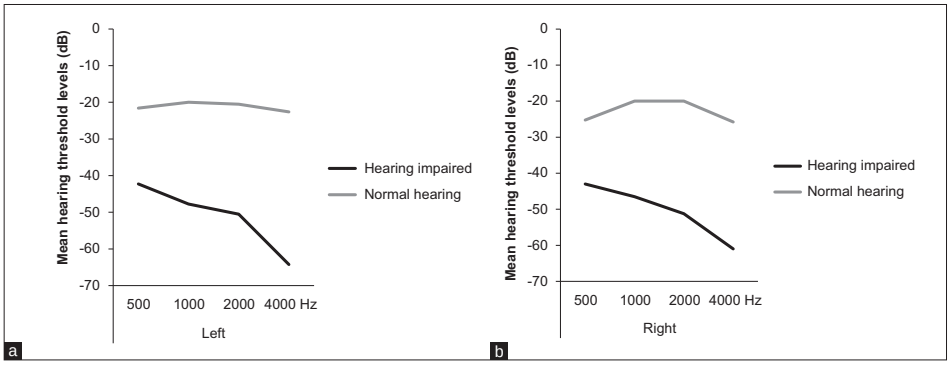
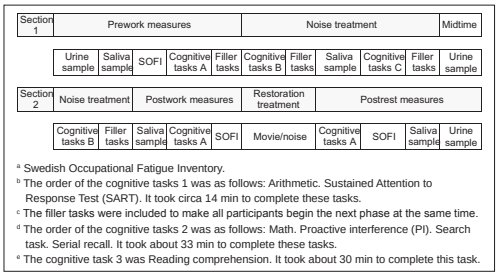


Figure 1: (A) Mean hearing threshold levels for the left ear of the hearing impaired and normal hearing group (B) Mean hearing threshold levels for the right ear of the hearing impaired and normal hearing group



[a] Swedish Occupational Fatigue Inventory.
[b] The order of the cognitive tasks 1 was as follows: Arithmetic. Sustained Attention to Response Test (SART). It took circa 14 min to complete these tasks.
[c] The filler tasks were included to make all participants begin the next phase at the same time.
[d] The order of the cognitive tasks 2 was as follows: Math. Proactive interference (PI). Search task. Serial recall. It took about 33 min to complete these tasks.
[e] The cognitive task 3 was Reading comprehension. It took about 30 min to complete this task.

Figure 2: Overview of the procedure for one experimental session

task and the difficult task) and the mean response time for the expressions (also divided in the easy task and the difficult task).

Word memory

Memory for words was measured with a Proactive interference (*PI*) task, which taps the ability to inhibit information that once was relevant for recall but has since become irrelevant for the task.[30] The participants learned words from eight lists with ten words each. The separate lists were composed of words drawn from the same category. After a given list of ten words had been presented, participants were required to free recall the words from the most recent list and ignore (suppress) words from earlier lists. We used the following categories: "fish and other water living creatures", "fruits and vegetables", "animals", "cloths and accessories", "kitchen- and gardening tools", "countries" and "cities in Sweden". The words were presented on the computer screen every 1000 ms and remained for 1000 ms. The orders of the categories within each experimental session were counterbalanced between participants. The following four scores were considered: (1) PI points: the sum of words recalled from the correct list; (2) PI pro: the sum of error words (i.e. from earlier lists); (3) PI lacking answers: the sum of words not remembered; and (4) PI other errors: the sum of error words (i.e. new words not coming from earlier lists).

Reading comprehension

The texts for the reading task were taken from the Swedish National University Aptitude Test. One sentence at a time was presented and the participant decided when the next sentence should be presented by clicking the space button. In 25 of the 43 sentences one word was missing and the participants were given a choice between four alternatives. Sometimes the information for the correct choice was in the text that no longer was on the screen, sometimes the information appeared on the screen simultaneously. The scores were the sum of correct answers and the time it took to complete the reading task.

When all the text was read, two variations of memory questions were posed. In the first set the participant was presented with a sentence and was asked to judge whether the sentence was taken from the text read or not. In some of these sentences an important word from the original text had been changed and in other sentences there was no similarity with the original text. Scores were the sum of correctly marked sentences. In the second set there were questions about the information stated explicitly in the text, (e.g. years, book titles, places, names). Scores were the sum of correctly marked details.

Search task

In this task participants had to locate a specific object among different information channels. The information was organized in a table. The seven columns contained information about price, location, area, year etc. The twenty rows kept together the information about a given object (e.g. a person, a house or a country). The participants were asked to find the object that met a set of criteria, either by using two columns (easy) or four columns (difficult). Therefore this task taps processes required to search through and understand the contents of a table with information, while successively updating and memorizing which information is most correct according to the target criterion. Each experimental block consisted of the twelve questions (e.g. six easy questions and six difficult questions) and time was limited to one minute per question before a new question was presented. The scores were the sum of correct answers (divided into the easy task and the difficult task) and the time it took to complete the search task (also divided into the easy task and the difficult task).

Serial recall

In this task with numbers, the participants were told to remember a string of eight one digit numbers (i.e. 1-8) and then recall them in the correct order. Each number was presented for 400 milliseconds followed by a pause of 350 milliseconds before the next number was presented. After the eight digits were presented an answer box appeared on the computer screen with the numbers 1-8 in random order. The participants then had to organize the numbers in the correct order. Each block consisted of 27 lists and only numbers written at their correct positions were scored correct. We also scored lists that were complete (e.g. when all the eight digits were assigned their correct positions).

Self ratings of fatigue

Perceived sleepiness and motivation were measured with the Swedish Occupational Fatigue Inventory (SOFI) developed by Åhsberg, Gamberale and Kjellberg.[31] The questions are based on a factor analysis where five components were established for 25 items describing feelings of cognitive- and physical fatigue. Only the three components describing cognitive fatigue were selected for this study. Lack of energy was measured with the words "worn out" and "exhausted", Lack of motivation with the words "passive"

and "uninterested", and Sleepiness with the words "sleepy" and "the number of yawns for the last ten minutes" on a scale ranged from 1 = not at all to 4 = a lot.

Stress hormones

Urinary catecholamine's

The urine samples were collected directly when all participants arrived to the laboratory (Pre work), in the middle of the work period (Mid work; after 1 hour 30 minutes) and at the end of the experimental session (Post rest; after 3 hours). For each participant, the exact time after the bladder had been emptied by voluntary voiding was noted, the total urine volume was measured, and 40 ml of urine was mixed in 100 ml glass bottles containing 0.5 ml 2 M HCL as a preservative. Samples were stored in a freezer at – 20°C until subsequent preparation. The samples were thawed within 2 months and purified according to the BIO-RAD method (Urinary Catecholamine's by HPLC, Reagent Kit, Catalogue Number 195-5841/N) and assayed following standard methods for high performance liquid chromatography. The amounts of the catecholamines Norepinephrine and Epinephrine were expressed as ng/h/kg body weight. The analyses were carried out by a professional blind to the experimental conditions at the University of Gävle.

Salivary cortisol

Saliva samples were obtained with Salivette tubes (Sarstedt, Landskrona, Sweden) at four times during the experimental session: Pre work, after approximately 1 hour of work, Post work and Post rest [Figure 2 for an overview of the experimental session]. It is however, unclear how to handle the timing of the measurements of the peak response in cortisol as there might be a time lag before the reaction is measurable.[32] The radio immunoassays (RIA) of the samples were carried out in the Stress Research Institute at Stockholm University by a professional blind to the experimental conditions.

Procedure

Data collection took place at a simulated office at the University of Gävle. Participants went through a practice session for one hour, several days in advance of the first experimental session. The practice session was meant to reduce possible training effects on the cognitive tasks. The experimental sessions only took place on Tuesdays and Wednesdays. The experimental sessions were run between four and seven pm and for each participant, one day separated the two sessions. The procedure for one experimental session is presented in [Figure 2].

After the first urine and saliva samples, the participants completed the SOFI and performed the first block of fatigue tasks in quiet. After the fatigue tasks they preceded through the first block of cognitive tasks while one of the two different noise conditions (low noise, or high noise) was played back. The session order of the noise conditions was counterbalanced but not the cognitive tasks between the experimental sessions. The Search task and Word memory task were counterbalanced between participants within one session to reduce the risk of an order effect because of the different task categories. After 1.5 hours of work the participants left the simulated office for the second urine sample. Back in the laboratory the second block of cognitive tasks started. Next, the second fatigue block started and the noise was turned off. In the beginning of this block a saliva sample was collected and the SOFI was again completed.

The next phase was the restoration period wherein the participants were instructed to put their headphones on. In the high noise condition the participants either watched a nature movie with no sound or listened to office noise (without any film) during the restoration period. The participants were randomly assigned to one of the two restoration conditions. In the low noise condition all participants sat in quiet for 14 minutes to keep the same session length. After the restoration period the participants put off their headphones and went through the last fatigue block in silence. The whole procedure took about three hours to complete and one to eight participants were tested at each occasion.

Statistical analyses

Because of failures to follow instructions 3 participants were excluded from the analyses of the noise effects, leaving 34 participants for further analysis. One participant was excluded from the analyses of the restoration effects due to equipment malfunctioning during the restoration period. There are further data missing for the following number of participants in these measures: SART (1), Reading comprehension (2), Search task (9), SOFI (4), Norepinephrine (3), and Epinephrine (3) due to lack of answers and equipment malfunctioning. A General Linear Model (SPSS version 18) with repeated measures (mixed) design was used for the analysis of noise and fatigue effects. When Mauchly's test indicated significant non-sphericity in the variance-covariance matrix for the within-subject analyses, the Greenhouse-Geisser adjusted degrees of freedom and corresponding *P*-values are reported for the *F*-tests.

Results

Results are reported first for effects during work, and then for the effects of restoration. For both sections the presentation order begins with the effects on cognitive performance, then on psychophysiological stress and then finally on self-ratings of fatigue.

Noise effects on cognitive performance during work

In the design, noise conditions (high and low) was a within-participant variable. However, given evidence that the performance measures showed strong transfer effects (i.e. interactions of performance and session order), we defaulted to treat noise conditions as a between-persons variable with

the high and low noise levels in the first experimental session as a between-participants variable.

Math

There were no significant effects of noise or hearing on the number of correct answers in the math tasks. This might be due to a ceiling effect since few participants had more than three errors. Further, the analysis showed no significant main effect of noise on speed. Therefore, there is no support for Hypothesis 1 (a) - that mathematical performance was impaired by noise level.

However, there was an interaction between noise and hearing on performance speed. As shown in Figure 3a both the hearing impaired- and normal hearing groups appeared to work faster in the easy tasks in high noise than in low noise. In the difficult tasks Figure 3b the hearing impaired appeared to work faster in high noise than in low noise, whereas the normal hearing groups performed at about the same speed in both high and low noise. An ANOVA with noise condition and hearing (2 × 2) as between-participants factors and time and difficulty (2 × 2) as within-participant factors showed the Noise × Hearing × Difficulty interaction to be significant (F (1, 30) = 4.62, $P < 0.05$, *partial* $\eta^2 = 0.13$). The interaction contradicts Hypothesis 2 because the hearing impaired worked faster in high noise than the normal hearing individuals. Also for the easy tasks the results were not in line with Hypothesis 2, as both hearing groups were faster in high noise.

Word memory

The analysis showed no significant main effect of Noise on the measures of word memory. This contradicts Hypothesis 1 (a) which predicts impaired performance during the higher noise level. Further, as shown in Figure 4, the hearing impaired participants appeared to do worse (had more omissions) in the word memory task (PI) during high noise, than in the low noise condition, whereas the opposite was true for the group with normal hearing. However, the ANOVA only showed a trend towards Hearing × Noise interaction F (1, 30) = 3.30, $P = 0.079$, *partial* $\eta^2 = 0.10$. The results thus showed a trend in line with Hypothesis 2, indicating that the hearing impaired had more difficulties in high noise compared to normal hearing individuals.

Reading comprehension

In contradiction to Hypothesis 1 (a) there were no main effects of noise on any of the reading scores. Again, only when hearing status was considered, an effect of noise level was seen.

As shown in Figure 5 the participants with a hearing impairment appeared to remember more sentences in low noise compared to those in high noise, while the normal hearing group showed the opposite effect. This was confirmed by the ANOVA, which showed a significant interaction between Hearing and Noise on memory for the contents (points for correctly marked sentences), F (1, 28) = 4.70, $P < 0.05$, *partial* $\eta^2 = 0.14$. Further, memory for specific details in the text (points of correctly marked details) showed a similar pattern, but in this case there was only a tendency toward a Hearing × Noise interaction, F (1, 28) = 3.28, $P = 0.081$, *partial* $\eta^2 = 0.11$. These results were in line with Hypothesis 2 showing that the hearing impaired had more difficulties in high noise than the normal hearing individuals.

Search task and serial recall

There were no statistically significant effects of Noise on the Search task and for Serial recall performance. The participants had only a few correct answers in the difficult part of the Search task which suggests a floor effect.

Noise effects on acute psychophysiological stress during work

Since there are large individual variations in stress hormone levels, the analyses of the physiological measures were only conducted with noise as a within-participant comparison. The mean cortisol level was gradually lowered between the three measurement occasions both in the low and the high noise conditions, F (1.31, 39.27) = 33.82, $P < 0.001$, *partial* η^2 =

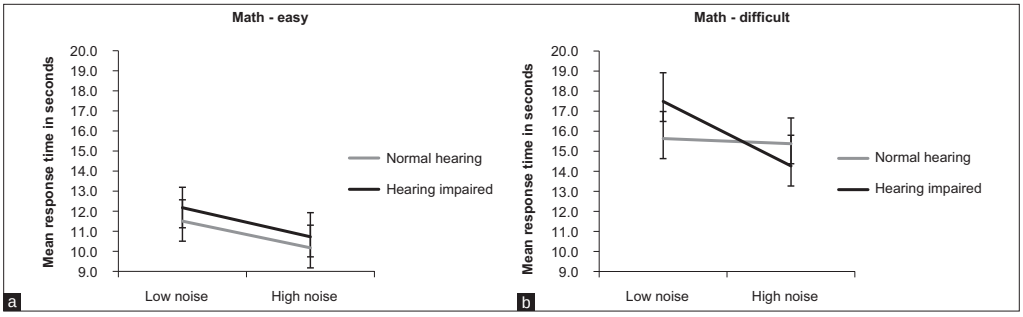


Figure 3: (A) Math performance in the easy task for the normal hearing and hearing impaired participants in high and low noise. Error bars are the standard errors of the mean (B) Math performance in the difficult task for the normal hearing and hearing impaired participants in high and low noise. Error bars are the standard errors of the mean

0.53, [Figures 6a and 6b]. There was no main effect of noise, but in low noise the hearing impaired and normal hearing participants had approximately the same cortisol levels at all measurement occasions, whereas in high noise the hearing impaired group had higher levels than the group with normal hearing. This was reflected in the ANOVA as a tendency towards a Time × Noise × Hearing interaction, F (1.37, 41.23) = 3.06, P = 0.075, *partial* η^2 = 0.093. In summary, we found no significant support for Hypothesis 1 (b) but a tendency towards higher stress levels during high noise exposure for the hearing impaired participants in line with Hypothesis 2.

Norepinephrine levels declined over time, F (1.28, 33.19) = 10.18, P < 0.002, *partial* η^2 = 0.28. However, there was no significant main effect of noise on the level of catecholamines over time and no interaction between noise and hearing. No support thus was found for Hypotheses 1 (b).

Noise effects on self ratings of fatigue during work

In this section the focus is only on the noise effects which were measured Pre work and Post work. In the section concerning restoration we also include measures from Post rest (after the period of restoration).

In the first step we analyzed the SOFI ratings with session order and hearing (2 × 2) as between-participant factors and noise and time (2 × 2) as within-subjects factors. The analysis revealed a significant main effect of time on all the scales, sleepy, F (1, 29) = 43.67, P < 0.001, *partial* η^2 = 0.60; the amount of yawning, F (1, 29) = 11.48, P < 0.01, *partial* η^2 = 0.28; worn out, F (1, 29) = 52.83, P < 0.001, *partial* η^2 = 0.65; exhausted, F (1, 29) = 42.38, P < 0.001, *partial* η^2 = 0.59; passive, F (1, 29) = 54.72, P < 0.001, *partial* η^2 = 0.65; and uninterested, F (1, 29) = 62.26, P < 0.001, *partial* η^2 = 0.68; indicating an increase of sleepiness, lack of energy and loss of motivation over time [Table 1]. However, the participants were more sleepy, tired and were less motivated over time during both high and low noise exposure, which contradicts Hypothesis 1 a of a main effect of noise level.

Further, the hearing impaired participants and the normal hearing participants rated themselves at about the same level of sleepiness during the low noise exposure. During the high noise exposure the hearing impaired were more sleepy than the normal hearing group Figure 7, yielding a significant Noise × Hearing interaction on the rating of the amount of yawning, F (1, 29) = 5.56, P < 0.05, *partial* η^2 = 0.16.

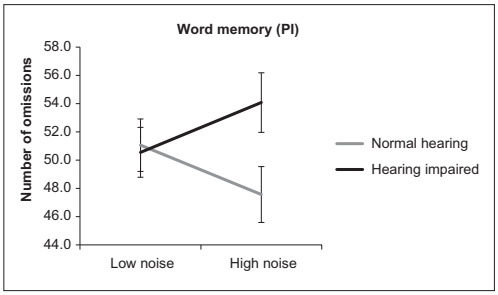


Figure 4: The number of omissions in the word memory task (PI) for the normal hearing and hearing impaired participants in low and high noise. Error bars are the standard errors of the mean

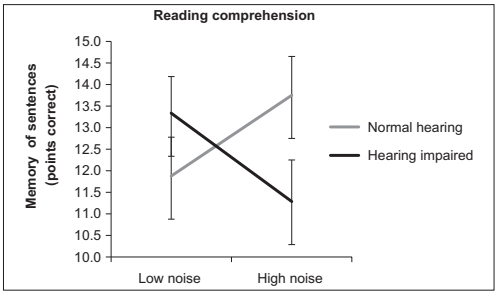


Figure 5: Memory of sentences in the reading comprehension task for the normal hearing and hearing impaired participants in high and low noise. Error bars are the standard errors of the mean

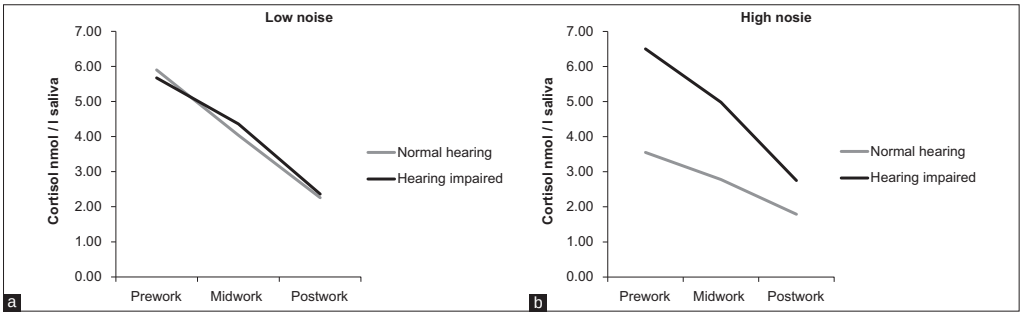


Figure 6: (A) Cortisol levels (nmol/l saliva) in low noise at Prework. Mid work and Post work (B) Cortisol levels (nmol/l saliva) in high noise at Pre work. Mid work and Post work

Unexpectedly, participants became more uninterested (unmotivated) over time in low noise than when they were in high noise, which resulted in a significant Time × Noise interaction on the ratings of being uninterested, F (1, 29) = 4.43, $P < 0.05$, *partial* $\eta^2 = 0.13$. Note also that the mean values indicated that the normal hearing participants were less motivated than the hearing impaired during both noise conditions Table 2; however, this Time × Noise × Hearing interaction was not significant.

In summary, the hearing impaired participants were more tired during high noise exposure than the normal hearing participants, which is in line with Hypothesis 2.

Effects of restoration on cognitive performance

As a first step we analyzed if the participants had a drop in arithmetic performance from Pre work to Post work during high noise to establish that the participants were in a state of need for cognitive restoration. Although discrepancies were found in performance between session orders, the overall pattern showed decreased quality and increased speed during work in high noise exposure. The ANOVA showed that the Time × Session order interaction was significant for both correct answers; F (1, 29) = 5.05, $P < 0.05$, *partial* $\eta^2 = 0.15$, and performance speed; F (1, 29) = 9.23, $P < 0.01$, *partial* $\eta^2 = 0.24$.

As a second step we analyzed whether there was a difference in performance between a restorative period with movie or noise from Post work to Post rest. As shown in Figure 8a the normal hearing participants performed better (correct answers) after restoration with a movie, while their performance declined after continued noise exposure. As shown in Figure 8b, the opposite pattern emerged for the hearing impaired participants with decreased performance with movie and improved performance with noise. An ANOVA with Restorative condition, Hearing and Session order (2 × 2 × 2) as between-participants factors and Time (2) as a within-participant factor, showed that the Restorative condition × Time × Hearing interaction was significant; F (1, 25) = 7.64, $P < 0.02$, *partial* $\eta^2 = 0.23$. In summary, only the normal hearing participants followed Hypothesis 3, with increased performance after restoration with the movie and decreased performance with noise.

Table 1: The mean and standard errors for the self-ratings (SOFI) at Pre work and Post work. The scale ranged from 1 = not at all to 4 = a lot

SOFI – Measure	Time	Mean	Std. Error
Sleepy	Pre work	1.54	0.10
	Post work	2.62	0.15
Worn out	Pre work	1.48	0.09
	Post work	2.33	0.11
Passive	Pre work	1.49	0.09
	Post work	2.44	0.13
Number of yawns	Pre work	1.30	0.08
	Post work	1.75	0.12
Exhausted	Pre work	1.43	0.09
	Post work	2.32	0.14
Uninterested	Pre work	1.40	0.11
	Post work	2.47	0.16

Table 2: The mean and standard errors for the self-ratings of lack of motivation (uninterested) at Pre work and Post work in high and low noise, for both hearing groups. The scale ranged from 1 = not at all to 4 = a lot

Hearing status	Time	Low noise		High noise	
		Mean	Std. Error	Mean	Std. Error
Normal hearing	Pre work	1.44	.17	1.69	0.19
	Post work	2.88	.24	2.50	0.24
Hearing impaired	Pre work	1.24	.16	1.25	0.19
	Post work	2.31	.24	2.21	0.24

Effects of restoration on acute psychophysiological stress

No effect of restoration was found on the urinary catecholamines and salivary cortisol, yielding no support for Hypotheses 3. However, see the effects of time on the urinary catecholamines and salivary cortisol under the section "Noise effects on acute psychophysiological stress" above.

Effects of restoration on self ratings of fatigue

As stated previously the participants were sleepy prior to the restorative period, as the participants showed a significant increase in sleepiness, a significant decrease in energy, and a significant loss of motivation from Pre work to Post work during both high and low noise exposure.

As shown in Figure 9a, the normal hearing participants had a loss in motivation (i.e. passiveness) after a restorative period in noise and an increase in motivation after they had watched the movie. However, the hearing impaired showed the opposite pattern with an increase in motivation after a restorative period in noise and a decrease with movie [Figure 9b]. An ANOVA with Restorative condition, Hearing and Session order (2 × 2 × 2) as between-participants factors and time (2) as a within-

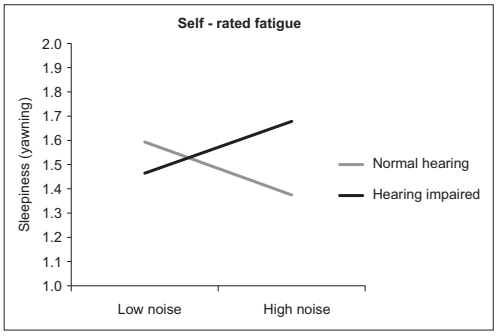


Figure 7: Self-ratings for sleepiness (yawning) for the normal hearing and hearing impaired participants in high and low noise. The scale ranged from 1 = not at all to 4 = a lot

participant factor showed that the Time × Hearing × Restorative condition interaction was significant for lack of motivation (passiveness); $F(1, 24) = 5.50$, $P < 0.05$, *partial* $\eta^2 = 0.19$.

For the other SOFI-variables there was a session-order interaction, which made us leave those analyses from further consideration.

In summary, only the normal hearing participants followed Hypothesis 3, with increased motivation after restoration with the movie and loss in motivation with noise.

Discussion

Effects of noise on cognitive performance

There were no main effects of noise level on any of the tasks (i.e. Math, Memory for words, Reading, Search task and Serial recall), contradicting Hypothesis 1 a. The high noise level tested was 60 L_{Aeq}, which is in the region of a normal speech level. However, when exploring the effects of hearing status, we found an interaction between hearing and noise level in line with Hypothesis 2 for two of the tasks. The hearing impaired participants were more affected by high noise than the normal hearing, as shown by decreased performance in memory for the contents of a text, and a tendency for decreased performance in the memory for words test. Possibly, noise at 60 L_{Aeq} was distracting for the hearing impaired as they presumably are more sensitive for noise.

An interesting result was also that the normal hearing participants worked better overall during high noise than low noise. One plausible explanation may be their motivational and arousal level. For example, Yerkes and Dodson's[33] theory predicts a need of a higher level of arousal for optimal performance on easy tasks than more difficult tasks (i.e. the "task difficulty hypothesis"). If most of the tasks we employed were perceived as quite easy to the participants they most probably needed arousing stimuli (i.e. noise) to perform well. In line with this, Suedfeld and Loewen[34] have showed that feelings of arousal can increase with noise. The subjective ratings also showed that the participants had significantly higher motivation in high noise than low noise, although sleepiness increased over time. However, there are some difficulties with these theories, particularly in specifying the optimum level of arousal.

One notable result was that the easy math tasks benefited from a higher noise level. In this task (i.e. adding two

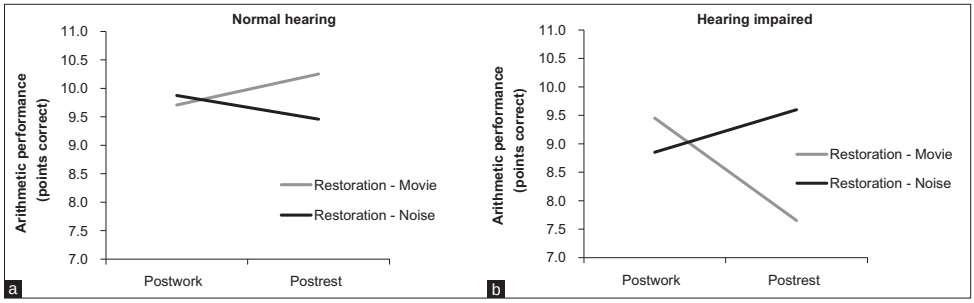


Figure 8: (A) Arithmetic performance in the restorative conditions movie and noise at Post work and Post rest, for normal hearing. The scale ranged from 0-12 pts of correct answers (B) Arithmetic performance in the restorative conditions movie and noise at Post work and Post rest, for hearing impaired. The scale ranged from 0-12 pts of correct answers

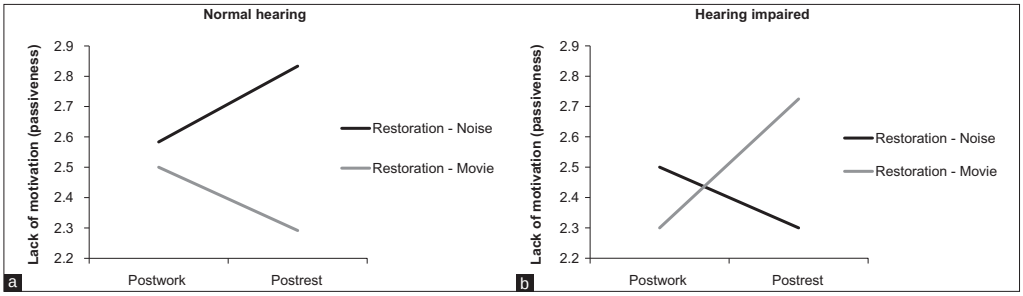


Figure 9: (A) Self-ratings for lack of motivation for the comparison movie vs. noise at Post work and Post rest for normal hearing. The scale ranged from 1 = not at all passive to 4 = very passive (B) Self-ratings for lack of motivation for the comparison movie vs. noise at Post work and Post rest for the hearing impaired. The scale ranged from 1 = not at all passive to 4 = very passive

digit numbers) both hearing impaired and normal hearing participants worked faster in high noise than in low noise. In the more difficult math task (i.e. adding three digit numbers) the hearing impaired participants worked faster in high noise, while the normal hearing participants worked at about the same speed in high and low noise. This benefit is in line with a previous study by Loed, Holding and Baker[35] which showed that background noise can increase performance of simple arithmetic's (i.e. speed in work completion) when performed during the afternoon. The present experiment was also conducted during the afternoon, therefore, the results appear to be consistent with an arousal explanation.

Another question that arises is why there was no interaction between noise level and hearing status for two of the tasks (i.e. Serial recall and Search task). The lack of an interaction with noise level may be explained by earlier studies showing that some tasks are not vulnerable to a variation in noise intensity; rather performance is impaired by the changing properties of the sound.[36] However, the tasks shown to be impaired by noise intensity when hearing status was considered (i.e. memory for contents of a text, memory for words), need more complex semantic processing and involvement of long term memory (e.g. processing of word meaning, rehearsal of solutions). This is in line with an earlier study[8] that also showed word memory (i.e. semantic memory) to be impaired by office noise level but not, for instance, serial recall. The present results therefore support the finding that only some tasks are impaired by office noise.[37] One important objective for future studies will be to decompose tasks into their component processes and then test the impact of different noise sources on those constituent processes.

Effects of noise on acute stress

The participants showed a significant decline in cortisol in both noise conditions over time, consistent with the decline that occurs as a part of normal circadian variation. However, there was a tendency for the hearing impaired participants to show higher stress levels over time in high noise compared to low noise. The same pattern of decline over the experimental session in both noise conditions was also evident in the norepinephrine, measured from urine. In summary, we found no main effect of noise on stress hormones, contradicting Hypothesis 1b. The results merely showed a weak tendency in line with Hypothesis 2 demonstrating that the hearing impaired participants were more stressed by the high noise condition compared to the normal hearing participants.

Effects of noise on self-ratings of fatigue

In both noise conditions there was an increase of sleepiness and loss of motivation over time. However, there was no main effect of noise level on fatigue, contradicting Hypothesis 1b. Instead there was an interaction between noise and hearing status in line with Hypothesis 2. During low noise both hearing groups were at about the same level of sleepiness. However, during high noise the hearing impaired were expected to be more tired than the normal hearing participants.

Restoration

The participants felt sleepier, less motivated and less energetic from Pre work to Post work, and their performance quality decreased in the arithmetic task during the work period. Thus, the results meet the criteria for analyzing cognitive restoration (i.e. an antecedent condition indicating fatigue).

It was shown that the normal hearing participants´ performance and motivation improved with the nature movie, and declined after continued noise exposure. This supports earlier findings[8] that normal hearing participants restore better with a nature movie than with noise. However, for the hearing impaired participants of the present study, the opposite pattern emerged. Both their performance and motivation decreased after restoration with the nature movie, and improved after noise exposure. This is difficult to explain, but one possible explanation is that continued noise exposure might have counteracted their possibilities to slow down, relax, and feel how sleepy they were.

Further, no restorative effects were found on the salivary cortisol and urinary catecholamines. The stress hormones showed a decline over time in accordance with the normal circadian rhythm.

In summary, Hypothesis 3 only held for the normal hearing participants' performance and motivation. They showed significantly increased performance and motivation after restoration with the movie and decreased performance and motivation with noise. The hearing impaired contradicted Hypothesis 3 with the opposite pattern.

A comparison with our previous experiment

Jahncke *et al*,[8] reported an experiment with open-plan office noise, cognitive performance, restoration and subjective ratings that in many respects is comparable to the experiment reported here. However, there are some discrepancies in the results, which may or may not be due to differences in the sounds employed, in the cognitive tests employed and/or the characteristics of the participants. For instance the participants in the previous study were young (mean age = 26 years) students at the University of Gävle, while the participants in the study reported here were older (mean age close to 50 years) and had less formal schooling and had different occupations. To probe whether this difference had any impact on the difference in results between the two experiments, a follow up statistical comparison was made between the results on a comparable test (i.e. serial recall) from participants in Jahncke *et al*,[8] and participants from the present study. This analysis showed that normal hearing participants in the study of Jahncke *et al*,[8] that were students, performed

better in low noise than the normal hearing participants in the present study, $t\ (53) = 2.27$, $P < 0.05$, although the low noise in Jahncke *et al*,[8] was 39 L_{Aeq} as compared to 30 L_{Aeq} in the present study. It should be noted that serial recall is rather insensitive to sound level.[36]

The baseline difference in performance level between the normal hearing groups, in the two experiments, may be one of the explanations as to why the results of the present study differ from the results of the earlier study by Jahncke and colleagues. It is however, difficult to further explain the discrepancies in our findings.

Limitations

It should be acknowledged that this study was small in scale and that we had additional problems with missing data. There is therefore a risk that the conclusions are underpowered. The lack of interactions especially may have been seriously influenced by the small N in our samples. It is possible that different results may have been found in a larger sample, especially when considering how much variation there may be in the hearing impaired group.

Further, we cannot tell whether we would have observed an increase in fatigue if we had not conducted our study from 4-7 pm. This for most office work would be towards the end of the working day and another choice of time frame might have changed the results. However, we choose to conduct these studies during the afternoon as this is more appropriate for measuring the stress hormones, as we expect a decrease in stress hormone levels in the afternoon. If the stress hormones are measured when a daily increase is expected we could not rule out whether the increase is due to noise or the circadian rhythm.

According to the stress hormones, most of the tasks employed were most probably perceived as quite easy to the participants. This could explain why we did not see any main effect of noise on the stress hormones in our study.

It can also be questioned if it is of real-life relevance to watch a nature movie with no sound as a tool to be used in real office life. Outside the experimental studies it is probably of better practical use to take a walk in a real nature environment during the break. Further, we are not able to say whether it is the silence, the nature, or both that are important as our stimuli contained both these features. This is something for future research to examine further.

Conclusion and Practical Implications

The results of this study showed that the hearing impaired were more distracted by high noise than the normal hearing, as indicated by decreased performance in the tasks requiring recall of semantic information. However, they were not distracted when they performed the two tasks (Serial recall and Search task) that are underpinned by processes, which previously have shown to be insensitive to noise level.

The hearing impaired individuals were also more fatigued by a higher noise exposure than people with normal hearing and they tended to have higher stress hormone levels during high noise compared to the low noise. The present study however, cannot disentangle whether the effects reported are a result of hearing impairment or a result of the use of hearing aids. The participants might also have used different types of hearing aids, which can differ in performance and suitability for our test conditions.[38]

An important finding in this study is that it is not just the types of noise and layout of the office that affect employees. The impact also varies with the hearing characteristics of the persons exposed to noise and the tasks they perform. Therefore, special consideration needs to be made to the individual prerequisites. For example, it is rarely possible for hearing impaired persons to decrease the negative impact from surrounding noise by turning off the hearing aids, when the work requires a readiness for phone calls and communication with colleagues. Therefore other solutions might be needed (e.g. quiet rooms) to be able to enhance performance and wellbeing for these individuals.

There should also be further concerns for designing sound environments that can promote daily restoration at workplaces, as indicated by an earlier study of Jahncke *et al*.[8] The present study showed that a break with a nature movie improved the normal hearing participants´ performance in arithmetic's, and that continued noise exposure during the break decreased their performance. These results underscore the need to address the issue of how to enhance restorative qualities within the noisy environments of our daily surroundings.

Acknowledgements

This research was funded by AFA Insurance and by the University of Gävle and was conducted in partial fulfillment of the requirements for a doctoral degree. We would like to thank Staffan Hygge and Terry Hartig for helpful advice in planning and conducting this study. We are also grateful to Kenth Dimberg at the University of Gävle for analyzing the urine samples and Lars Holmberg at the Stress Research Institute, Stockholm University for analyzing the saliva samples. We also thank Örjan Johansson and Johan Odelius at Luleå University of Technology for their help with the recordings and arrangements of the office noise used in this experiment and to Valtteri Hongisto and David Oliva for their help with analyzing the STI of speech in the office noise recordings. We also thank Anders Kjellberg, John Marsh, Patrik Sörqvist and the anonymous reviewers for helpful comments on this manuscript, the Swedish Association of Hard of Hearing People (HRF) for generous support, and Ecophon and S-line office for their donations to furnish the simulated open-plan office.

Address for correspondence:
Ms. Helena Jahncke,
Department of Environmental Psychology, Faculty of Engineering and Sustainable Development, University of Gävle, SE-801 76 Gävle, Sweden.
E-mail: helena.jahncke@hig.se

References

1. Navai M, Veitch JA. Acoustic satisfaction in open-plan offices: Review and recommendations *(IRC-RR-151)*. Canada: National research council Canada, Institute for research in construction; 2003.
2. Oommen VG, Knowles MK, Zhao IZ. Should health service managers embrace open plan work environments? A review. Asia Pac J Health Manag 2008;3:37-43.
3. Rashid M, Zimring C. A review of the empirical literature on the relationships between indoor environment and stress in health care and office settings: Problems and prospects of sharing evidence. Environ Behav 2008;40:151-90.
4. Haka M, Haapakangas A, Keränen J, Hakala J, Keskinen E, Hongisto V. Performance effects and subjective disturbance of speech in acoustically different office types - A laboratory experiment. Indoor Air 2009;19:454-67.
5. Schlittmeier S, Hellbrück J, Thaden R, Vorländer M. The impact of background speech varying in intelligibility: Effects on cognitive performance and perceived disturbance. Ergonomics 2008;51:719-36.
6. Sörqvist P, Halin N, Hygge S. Individual differences in susceptibility to the effects of speech on reading comprehension. Appl Cogn Psychol 2009;24:67-76.
7. Evans GW, Johnson D. Stress and open-office noise. J Appl Psychol 2000;85:779-83.
8. Jahncke H, Hygge S, Halin N, Green AM, Dimberg K. Open-plan office noise: Cognitive performance and restoration. J Environ Psychol 2011;31:373-82.
9. HRF: S årsrapport 2008: ”Adjö yxskaft” [HRF´s annual report 2008: “What’s that got to do with the price of fish?”]. HRF – the Swedish association of hard of hearing people. c2008 -. Available from: http://www.hrf.se. [Last cited on 2012 Jan].
10. Moore BC. Speech processing for the hearing-impaired: Success, failures, and implications for speech mechanisms. Speech Commun 2003;41:81-91.
11. Larsby B, Hällgren M, Lyxell B, Arlinger S. Cognitive performance and perceived effort in speech processing tasks: Effects of different noise backgrounds in normal-hearing and hearing-impaired subjects. Int J Audiol 2005;44:131-43.
12. Rakerd B, Seitz PF, Whearty M. Assessing the cognitive demands of speech listening for people with hearing losses. Ear Hear 1996;17:97-106.
13. Arlinger S. Störning av talkommunikation [Disturbance of spoken communication]. In: Arbete och hälsa 1999:27 Störande buller - Kunskapsöversikt för kriteriedokumentation [Work and health 1999:27 Disturbing noise - A knowledge survey for criteria documentation, not available in English]. Stockholm: Arbetslivsinstitutet; 1999.
14. Harris JD. A brief critical review of loudness recruitment. Psychol Bull 1953;50:190-203.
15. Hughes RW, Vachon F, Jones DM. Disruption of short-term memory by changing and deviant sounds: Support for a duplex-mechanism account of auditory distraction. J Exp Psychol Learn Mem Cogn 2007;33:1050-61.
16. Babisch W. Stress hormones in the research on cardiovascular effects of noise. Noise Health 2003;5:1-11.
17. Melamed S, Bruhis S. Effects of chronic industrial noise exposure on urinary. Cortisol, fatigue, and irritability: A controlled field experiment. J Occup Environ Med 1996;38:252-6.
18. Persson-Waye K, Bengtsson J, Rylander R, Hucklebridge F, Evans P, Clow A. Low frequency noise enhances cortisol among noise sensitive subjects during work performance. Life Sci 2002;70:745-58.
19. Ulrich RS. Aesthetic and affective response to natural environment. In: Altman I, Wohlwill JF, editors. Behavior and the natural environment. New York: Plenum Press; 1983. p. 85-125.
20. Kaplan R, Kaplan S. The experience of nature: A psychological perspective. New York: Cambridge University Press; 1989.
21. Hartig T. Three steps to understanding restorative environments as health resources. In: Ward Thompson C, Travlou P, editors. Open space: People space. New York: Taylor and Francis Inc; 2007.
22. Kaplan R. The role of nature in the context of the workplace. Landsc Urban plan 1993;26:193-201.
23. Berman MG, Jonides J, Kaplan S. The cognitive benefits of interacting with nature. Psychol Sci 2008;19:1207-11.
24. Laumann K, Gärling T, Stormark KM. Selective attention and heart rate responses to natural and urban environments. J Environ Psychol 2003;23:125-34.
25. Bowler DE, Buyung-Ali LM, Knight TM, Pulin AS. A systematic review of evidence for the added benefits to health of exposure to natural environments. BMC Public Health 2010;10:456.
26. Holding DH, Baker MA. Toward meaningful noise research. J Gen Psychol 1987;114:395-410.
27. Swedish standard, designation SS-EN 12464-1. Ljus och belysning - Belysning av arbetsplatser - Del 1: Arbetsplatsens utformning [Light and lighting - Lighting of work places - Part 1: Workplace Design]. ICS code 91.160.10; Stockholm: Swedish standards institute 2003.
28. Manly T, Robertson IH, Galloway M, Hawkins K. The absent mind: Further investigations of sustained attention to response. Neuropsychologia 1999;37:661-70.
29. Banbury S, Berry DC. Disruption of office-related tasks by speech and office noise. Br J Psychol 1998;89:499-517.
30. Craik FI, Birtwistle J. Proactive inhibition in free recall. J Exp Psychol 1971;91:120-3.
31. Åhsberg E, Gamberale F, Kjellberg A. Upplevd trötthetskvalitet vid olika arbetsuppgifter. Utveckling av ett mätinstrument [Perceived fatigue quality during different work tasks. Development of a measure]. Stockholm: Arbetsmiljöinstitutet; 1995. No. 20.
32. Dickerson SS, Kemeny ME. Acute stressors and cortisol responses: A theoretical integration and synthesis of laboratory research. Psychol Bull 2004;130:355-91.
33. Yerkes RM, Dodson JD. The relation of strength of stimulus to rapidity of habit-formation. J Comp Neurol Psychol 1908;18:459-82.
34. Suedfeld P, Loewen LJ. Cognitive and arousal effects of masking office noise. Environ Behav 1992;24:381-95.
35. Loeb M, Holding DH, Baker MA. Noise stress and circadian arousal in self-paced computation. Motiv Emot 1982;6:43-8.
36. Tremblay S, Jones DM. Change of intensity fails to produce an irrelevant sound effect: Implications for the representation of unattended sound. J Exp Psychol Hum Percept Perform 1999;25:1005-15.
37. Hongisto V. A model predicting the effect of speech of varying intelligibility on work performance. Indoor Air 2005;15:458-68.
38. Gatehouse S, Naylor G, Elberling C. Benefits from hearing aids in relation to the interaction between the user and the environment. Int J Audiol 2003;42:77-85.

How to cite this article: ???

Source of Support: This research was funded by AFA Insurance and the University of Gävle, **Conflict of Interest:** None declared.

Paper III

Accepted manuscript *Applied Acoustics* (2012)

Cognitive performance during irrelevant speech: Effects of speech intelligibility and office-task characteristics

Helena Jahncke[1], Valtteri Hongisto[2], & Petra Virjonen[2]

[1] *Environmental Psychology, Faculty of Engineering and Sustainable Development, University of Gävle, Sweden.*
[2] *Finnish Institute of Occupational Health, Indoor Environment Laboratory, Turku, Finland.*

Submission date: 16-5-2012
Review completed: 14-8-2012
Accepted date: 17-8-2012
DOI: 10.1016/j.apacoust.2012.08.007

Abstract

In open-plan offices, it is common that colleagues talk in the background while non-auditory tasks need to be performed. The aims of the present study were, first, to investigate how much cognitive performance is impaired by irrelevant background speech with varying degree of speech intelligibility, and second, to determine whether some office-related tasks are more susceptible to distraction than others. We tested a model developed by Hongisto [1] which predicts the decrease of cognitive performance as a function of speech intelligibility, depicted by the Speech Transmission Index (STI). Our results showed that the shape of the STI-performance curve, and the magnitude of the performance decrease, depend on task type. A semantic short-term memory task (i.e. word memory) was more sensitive to disruption by speech than a mathematical task. A word fluency task (i.e. retrieval of information from semantic long term memory) was not influenced by varying speech intelligibility. Moreover, performance on an information search task was impaired by speech with high intelligibility only. The steepest slope in performance decrease appeared at a lower speech intelligibility value than predicted by Hongisto [1]. It also varied between cognitive tasks. The results of this study are useful in determining an appropriate target level for acoustic design in offices: This work demonstrates that attempts to minimize speech intelligibility will yield increases in cognitive performance with a varying degree, depending on the type of focal task.

Keywords: auditory distraction; speech transmission index; working memory; long-term memory

1. Introduction

Performance in memory based and non-memory based cognitive tasks declines during the exposure to normal levels, 51 dB (L_{Aeq}), of office noise compared to lower levels, 39 dB (L_{Aeq}) of the same noise [2]. The most disturbing noise source in open-plan offices, both with respect to wellbeing and performance, is other people's speech (for a review, see Kaarlela-Tuomaala et al. [3]). Sound absorption materials, screens and artificial systems designed to mask sound are commonly used to reduce distraction from irrelevant speech and to improve speech privacy [4]. The overall noise level is not always the most important issue when assessing the acoustic environment in open-plan offices. An important factor is also the speech intelligibility of background speech [1].

According to the interference-by-process account of auditory distraction, the distraction is caused by a conflict that emerges between similar, competing processes [5]. Specifically, involuntary processing of the sound (e.g., interpreting the meaning of speech) produces distraction on tasks that necessitates the same, but deliberate, processes (e.g., interpreting the meaning of written prose). Tasks that do not involve similar processes as that involved in processing the sound, however, should not be susceptible to distraction by sound. For instance, when a task involves processing of order information, it is vulnerable to sounds which change across time, as the unavoidable processing of the order of changes in the sound interferes with the processing of serial order in the task [6]. In contrast, when a task does not involve serial order processes, it is not susceptible to distraction by order information conveyed by the sound [7]. This irrelevant sound effect (ISE) is well documented, especially for the serial recall task, in which a sequence of numbers is to be remembered and recalled in the order of presentation [8].

Further, when a task involves processing of semantic information (i.e. reading a text) the task is more vulnerable to speech sounds, as speech sounds are also semantically processed [5,9]. In the present study we will incorporate cognitive tasks that are more applied and resemble more typical office work, though they still involve seriation (the process of serially-ordering to be remembered material) and semantic processing, such as a search for information task and a math task.

Hongisto [1] has sketched a model of the function between Speech Transmission Index, STI, and performance on some cognitive tasks (e.g. serial recall, proofreading and reading comprehension). The Speech Transmission Index is an objective predictor of subjective speech intelligibility [10]. The STI values range between 0 and 1. A more detailed description of STI is

presented in Section 2.4.2. The model has been formulated by Hongisto et al. [11] and is shown in Figure 1.

However, the model was based on a review of only a few experimental studies where task performance was measured at a couple of STI levels and the experimental data was collectively fitted to a sigmoidal model. According to Figure 1, the magnitude of successful task performance will start decreasing when STI exceeds 0.2 and the largest decline will be reached above 0.50 (0.00 = not intelligible; 1.00 = perfectly intelligibly speech). The basic idea of the model has been applied in a recently published international room acoustic measurement standard for open-plan offices [16] and in the Finnish acoustic design guideline for open-plan offices [17]. Some recent studies have, to a certain extent, supported the model [14,15].

Hongisto's model has some distinctive characteristics. First, it makes a quantitative prediction about how much performance will decrease when the STI of the irrelevant speech increases, the maximum being a 7% decrease (i.e. difference in error percentage between silence and speech) for the tasks summarized. Second, the model assumes a steep linear slope in the middle of the STI-values and a flattening around the high and low STI-values. This implies that a test of the model should compare the linear, quadratic and cubic trends of the function between STI and performance.

In the current paper, the foregoing predictions of Hongisto's model—and the applicability of the model in the broader sense—will be tested using an experimental design with a larger body of cognitive tasks than was originally included in the review of Hongisto [1]. There are two issues that we elaborate in the present study. First, performance in the steep middle segment of the STI curve, and at which higher and lower STI values the curve levels out, will be studied. Exploring this area would be particularly informative. Second, it was stated by Hongisto [1] that this model might not apply to all kinds of cognitive tasks, and should be tested experimentally in the future within the field of cognitive psychology. It can, for example, be argued that tasks with specific characteristics might be more susceptible to variations in intelligibility of background speech than other tasks. Therefore, the extent to which the tasks involve certain characteristics (e.g. search for relevant information, to count, to remember material and to generate words) may be related to the precise point on the STI curve at which the maximum performance reduction will be reached.

The aim of the present study is to further specify the function of speech intelligibility and performance in the STI range from 0.10 to 0.40, where the most significant changes in performance are expected to occur, and see whether the STI-performance functions differ

between cognitive tasks. The STI of speech was adjusted by changing the signal-to-noise ratio of a single speaker with speech masking sound, which resembled ventilation noise.

We have selected four tasks which tap some fundamental characteristics of office work: to remember material (called Word memory task), to search for relevant information amongst distractors (called Information search task), to count (called Math task), and to generate words (called Word fluency task).

Specifically, our hypotheses are the following:

Hypothesis 1: The task performance depends on the STI of speech in such a way that the performance decrement starts around STI 0.20 and flattens out above STI 0.50. It is expected that the shape of the performance versus STI function will conform to Figure 1.

Hypothesis 2: The maximum performance decrement achieved at high STI values depends on task type. That is, the maximum performance decrement is not 7 % for all task types as Figure 1 suggests.

2. Materials and methods

2.1 Design

The hypotheses were tested by using a within-participants design with six acoustic conditions (STI 0.00, 0.08, 0.16, 0.23, 0.34, 0.71) and four tasks with different office-work characteristics (verbal fluency, word memory, information searching and counting) as dependent variables.

2.2 Participants

The participants were 47 persons with normal hearing and vision recruited from the University of Gävle. Five of the participants were excluded because one of the persons in one of the groups disrupted the others, leaving 42 (18 female) for the statistical analyses (mean age 24 years). Seven to eight participants were tested at the same time except during the session with disruptions. Participants were informed of the nature of the study before participating and they were rewarded with 500 SEK after their participation.

2.3 Research setting

The research was carried out in an office laboratory (60 m^2) at the University of Gävle. The room was designed to resemble an open-plan office including windows with artificial outdoor lighting. The workstations were separated by 1.43 m high screens. Each cubicle was 1.24 m wide. Ambient conditions of the indoor environment were kept fairly constant throughout the

experiments. The room temperature was around 21°C and the CO_2 concentration was always well below 1000 ppm. Vertical luminance was set to 480-520 lx on the height of the seating in each workstation and met the current recommendations in Sweden for work with computers [18]. The background noise level in the room was damped to approximately 30 dB (L_{Aeq}) not to disturb the acoustic condition STI 0.00 (silence condition) wherein the sound level played by the headphones was only 33 dB (L_{Aeq}).

2.4 *Acoustic conditions*

2.4.1 Speech sounds

The original speech material consisted of 120 different four-word sentences spoken by a female actress and 120 different sentences spoken by a male actor, thus yielding 240 sentences. These sentences were spoken in Swedish and taken from the Hagerman test [19], which is part of a package of standardized tests for speech audiometry. The sentences were balanced as they all contain the same number of objects, names, verbs etc. (e.g. "Japanese cars are cheap."). The duration of each sentence was three seconds. The speech recording was made in anechoic conditions at a distance of approximately one metre from the mouth using a 1/2-inch free-field microphone (Brüel & Kjaer 4190). The total amount of anechoic speech material was 12 minutes.

To create a realistic impression of speech heard from a nearby workstation in an open-plan office, the anechoic sentences were re-recorded in a small open-plan office in Turku. The room has been described in Haapakangas et al. [20]. The anechoic monophonic sentence files were played back one after the other through a loudspeaker (Genelec 8020) in one desk and recorded binaurally in another desk with a head and torso simulator (B&K 4100). This evaded moderate reverberation changes and binaural effects due to head movements. In all, the acoustic conditions resembled a situation wherein the participant was sitting in an office desk listening to speech from the opposite desk. The distance between the listener and the speaker was 2.2 metres and they were separated by a 1.3 m high screen. Thereafter, the binaural sentence files were arranged into 25 sentence lists (5 tasks for 5 STI levels including speech), where the sentences were separated by a 1000 ms pause. The length of the sentence lists was designed to exceed the time it would take to complete the tasks by at least five minutes. The same sentences were used multiple times in a sentence list to obtain sufficiently long lists. Their presentation order was pseudo-randomized (i.e., no more than three female or three male sentences were presented consecutively and the same sentence was separated by at least three other sentences).

2.4.2 Acoustic conditions

One way to depict how well speech is perceived in a certain room acoustic condition is to use the *Speech Transmission Index***,** STI [10]. Speech is perfectly intelligible when STI reaches 1.00 and completely non-intelligible when STI is 0.00. STI reduces with increasing reverberation time and increasing background noise level, because they interfere with the original speech signal. The STI method takes the room reverberation and background noise effects automatically into account. The equations behind the determination of STI are given, for instance, in Larm (at present: Virjonen) and Hongisto [21] and will not be repeated here. Subjective speech intelligibility of a specific STI value is dependent on whether speech items are syllables, words or sentences [1]. For example, perfect speech intelligibility of sentences is achieved at lower STI values than for words or syllables because of the greater semantic content that can be used as cues to perception. Hongisto's model assumes that the intelligibility of full sentences is of main importance in applied settings as normal speech typically consists of full sentences. The sigmoid model of Figure 1 uses the relation of sentence intelligibility and STI as published in [10].

We tested the effects of solo speech at six levels of STI. The planned STI values of the acoustic conditions were 0.00, 0.08, 0.16, 0.23, 0.34 and 0.71, respectively. STI 0.00 was a reference condition where speech was absent. It represented silence during which very silent masking sound was played at almost unnoticeable level of 33 dB (L_{Aeq}) corresponding with silent ventilation noise in typical office rooms. The other five conditions contained speech and masking sound of varying pressure level, while maintaining a constant total sound level of 51 dB (L_{Aeq}). This level is the typical overall activity noise level in open-plan offices [3]. The STI values were chosen to cover the critical area of STI where a drop in performance was expected to take place (STI below 0.30). STI 0.71 was a reference condition of speech with perfect sentence intelligibility.

The STI of the acoustic conditions including speech was changed by varying the signal-to-noise ratio of speech and masking sound (Table 1). The STI distribution in the acoustic conditions containing speech is presented in Figure 2. The distribution was determined by defining the STI of every sentence individually. To elucidate the normal variation of the STI and speech level between individual sentences, an example is given from the acoustic condition STI 0.71, presented in Figure 3. The time-averaged spectra of speech and masking sound in the acoustic conditions are presented in Figure 4.

2.4.3 Determination of STI

The STI of speech was determined according to the procedure of Houtgast and Steeneken [22] which is also applied in the measurement standard for open-plan offices [16]. The STI was determined for each binaural sentence. The modulation transfer functions (MTF) were measured for the workstation pair used in the binaural recording (WinMLS 2004). The early decay time (EDT) of the office room used for binaural recordings in Turku was 0.32, 0.37, 0.36, 0.28, 0.31, 0.32, and 0.27 in octave bands 125 – 8000 Hz. This represents the early decay time measured in highly sound-absorbing open-plan offices [4].

The speech level of reverberant speech sentences was determined in octave bands (Brüel & Kjaer SQ 14.1.1) for the left and the right ear separately and they were averaged. STI was calculated for each sentence using the measured MTF and the average speech and background noise levels.

The variation of STI between sentences (Figures 2 and 3) is a normal feature of speech. The sentences were short and all phonemes and consonants of the Swedish language were not present in each sentence. Therefore, the octave band spectrum of every sentence was different. This results in minor changes between the STI of the sentences even if the A-weighted sound level of the sentences would be constant. However, the acoustic conditions were successfully implemented since the average STI values and related standard deviations did not overlap significantly between successive acoustic conditions.

2.4.4 Sound tracks and the addition of masking sounds

The final sound tracks, which were played in the experiment, were created by mixing the binaural sentence lists with masking sound of adequate level (Adobe Audition 3.0). The masking sound was anechoic and monaural filtered pink noise (Adobe Audition 3.0). The spectrum of the masking sound was adjusted to – 5 dB per octave band (Brüel & Kjaer SQ 14.1.1) as suggested by a recent study by Haapakangas et al. [20]. The sound resembled comfortable ventilation noise. Altogether, 25 sound tracks containing speech were prepared. The 26th sound track represented the silence condition (STI 0.00).

The sound tracks were presented via headphones (Philips SHP8900) using the VLC- media player software (VLC 0.9.9, VideoLAN Organization, 2009). The computer managed the starting and stopping of sound playback. After the completion of each task, the playback of the sound track was stopped until the beginning of the next task. The equivalent sound level of each sound track containing speech was adjusted to 51 dB (L_{Aeq}). The level at both ears, respectively,

was checked using the head and torso simulator (B&K 4100) in each workstation, using a calibration signal stored at the end of each track.

2.5 Cognitive tasks

2.5.1 Word memory task

Memory for words was measured with a simple short-term memory task. Short-term memory has relevance for office workers as they need to keep their memory updated daily with the information of importance. The participants were visually-presented with words from eight lists comprising ten words each. The lists were composed of words drawn from the same semantic category (e.g., "animals"). After being presented with a given list of ten words, the participants were required to immediately recall the words from the most recent list in free order. This task puts substantial demands on both encoding and retrieval processes in semantic short-term memory. Each experimental block (i.e. six blocks) consisted of diverse categories: "fish and other water living creatures", "fruit and vegetables", "animals", "food and beverages", "countries" and "cities in Sweden". For the practice session we used the category "cars". The words were presented sequentially on the computer screen, one every 1000 ms and were each visible for 1000 ms. The order of the categories was counterbalanced between participants and acoustic conditions. The scores were the sum of correct answers and the task took approximately six minutes to perform.

2.5.2 Information search task

This task was originally designed to have relevance for office work as it taps processes required to search through and understand the contents of a table of information, while successively updating and memorizing information that accords with a target criterion [23]. The table contained twenty rows and seven columns. For each row, an object was presented (e.g., a person, a house or a country), and each column described one aspect of the object (price, location, year, etc.). The participants were asked to find the object that met a set of criteria, by using three of the seven columns (e.g. "Which building of row house type was built after the 70-s and is the most expensive?"). Each experimental block (i.e. six blocks) consisted of twelve questions (the same table was used for each question) and the time was limited to one minute per question before a

new question was presented. The scores were the sum of correct answers and the task took 12 minutes to perform.

2.5.3 Math task

This task was a simple addition task where participants were instructed to add triple-digit numbers, e.g. 146+309 [23]. Each experimental block (i.e. six blocks) consisted of 25 triple-digit expressions presented one by one together with an answer box. Every second expression had two carry over operations and the others had one carry over operation. The carrying component of mental arithmetic can place demands on inhibition and memory processes of interim results in working memory [24], depending on how the expression is solved. Some kind of episodic or working memory is therefore required (i.e. storage of a solution). Each experimental block (i.e. six blocks) consisted of diverse numbers to sum. The time limit for each expression was 18 seconds, after which the computer program continued to the next expression if an answer was not registered. The scores were the sum of correct answers. The task took approximately 7 minutes to perform.

2.5.4 Word fluency tasks (semantic- and phonemic fluency)

The word fluency task (method used by Troyer et al. [25]) consists of two tasks: semantic- and phonemic fluency, which make similar demands on retrieval from long term memory but rely on different activation and search processes [9]. As both tasks are based on long term memory, none of them involve rehearsal of to-be-remembered material. These two tasks are also relevant for office work in the respect that they tap processes to generate written texts and ideas.

In more detail, the procedure for the *Semantic fluency* task required participants to generate (write) as many exemplars from a given semantic category as possible within 60 seconds. Directly after the first category, another category was presented with the same time limit for responses. We used the category norms of Van Overschelde et al. [26] to select categories. For each of the six versions of the task developed for the present experiment, one category was taken from within the category mean potency rank number 33-38 (i.e. mean frequency of generated words was 5.7-5.8 words) and one was taken from within the rank number 44-50 (mean frequency of generated words was 5.2- 5.3 words) to keep the difficulty level fairly constant between the versions of the task. The selected categories were: a thing that flies; a substance for flavoring food; a liquid; a weapon; a carpenter´s tool; a type of human dwelling; a type of reading material; a tree; a type of fabric; an alcoholic beverage; a toy; and a type of dance. The scores were the sum of correctly generated words and the task took two minutes to perform.

In the *Phonemic fluency* task the participants were presented with a letter and instructed to generate as many words beginning with that letter as possible during 60 seconds. However, they were not allowed to generate variants of the same word: e.g., sail, sailing, and they were told to avoid producing proper nouns (e.g. names of places, people and products). The letter selection for the phonemic fluency task was based on a study by Borkowski, Benton and Spreen [27] that defines the difficulty level of the letters according to the frequency of the candidate words. In each of the six versions of the task two letters were presented. One letter was taken from the easy range category of difficulty (i.e. H, D, M, A, B, F) and one from the moderate range category (i.e. O, N, E, G, L, R), to keep the difficulty level fairly constant between the versions of the task. The scores were the sum of correctly generated words and the task took two minutes to perform.

2.6 Procedure

The participants were first instructed about voluntarily participation and the anonymity of their results. When the participants were seated in the open-plan office they were told to put on their headphones. They were instructed to wear them during the whole session and adhere to specific instructions. They were further told that they were not allowed to speak with each other and that the experimental instructor would be present in the room during the whole experiment (behind a wall screen). The session started with computerized background questions, followed by a practice period of all tasks for five minutes in silence. Every participant conducted the five tasks in the six acoustic conditions, that is, altogether 30 tasks. The tasks and the acoustic conditions were presented in randomized order generated by the computer for each participant (i.e. the participants had different procedures within the experiment); with the constraint that two of the same tasks were not presented consecutively and not more than three successive tasks occurred in the same acoustic condition. Each task started with an instruction in quiet (without masking). After half of the time the participants had a 15 minute break in another room. The whole procedure took about 3h 15 minutes.

2.7 Statistical analyses

The performance in each STI level was directly converted to percentages of maximum number of correct answers, P_{STI} [%]. For the word memory, information search, and math task, the maximum score was the maximum possible score (i.e. word memory: 80, information search: 12, math: 25). For the two word fluency tasks (semantic-, phonemic fluency), the best score

generated by a participant during the acoustic condition where the best performance was achieved, was used as the maximum score (i.e. 30 was used for both tasks). This maximum score was different to the other tasks as there are no obvious limits in word generation.

The absolute performance change, DP, was calculated as the difference in performance between the acoustic condition containing speech (non-zero STI values) and silence using the equation: $DP=P_{STI}-P_{0.00}$. The data presented in Figure 1 was also determined using this definition.

A General Linear Model (GLM, SPSS version 18) with repeated measures design was used for testing the first hypothesis. When Mauchly's test indicated non-sphericity in the variance-covariance matrix for the within-subject analyses, the Greenhouse-Geisser adjusted degrees of freedom and corresponding *p*-values are reported for the *F*-tests. When the form of the STI-performance function was tested, unequal spacing between the STI values was adopted by specifying the values (00, 08, 16, 23, 34, 71) in the Polynomial contrast. This was done to avoid inflated steepness between the steps 34 and 71.

For testing Hypothesis 2 (7% performance decrement) we used one-way paired *t*-tests as these comparisons were planned in advance and not *a priori*.

3. Results

3.1 Main findings over all tasks and acoustic conditions

A GLM analysis with acoustic condition and task (6×5) as within-participants factors with unequal spacing between the acoustic conditions revealed a significant main effect of acoustic condition, F (4.2, 170) = 5.20, $p < 0.001$, partial $\eta^2 = 0.11$. This indicates that performance varied over acoustic conditions, which is in accordance with Hypothesis 1. Further, there was a significant main effect of task, F (2.2, 89) = 41.4, $p < 0.0001$, partial $\eta^2 = 0.50$, indicating that the Math task was the easiest task while the Word memory task was the most difficult one (Figure 5).

As shown in Figure 6, performance did not change in the STI range 0.00 to 0.23. This is in agreement with the model of Hongisto [1] (Figure 1). However, the maximum decrease in performance was already achieved around STI 0.34. Figure 1 suggested that performance decrement would continue until approximately STI 0.50, above which the curve flattens out.

We also analyzed whether the steepest slope of the impaired performance flattened out at one end of the STI-spectrum (quadratic components) or at both ends (cubic components). When analyzing the form of the function for STI and performance (all tasks grouped together) we

found a significant linear trend, F (1, 41) = 14.2, $p < 0.001$, *partial* $\eta^2 = 0.26$, and a significant cubic trend, F (1, 41) = 4.2, $p < 0.05$, *partial* $\eta^2 = 0.10$. As indicated by Figure 6, there is a linear decrease in performance between STI 0.16 to 0.34. Further, the significant cubic trend indicates a knee around STI 0.16 and another knee from STI 0.34 where the curve flattens out. The STI – performance function for each task separately is shown in Figure 5.

Next, we investigated each task independently and tested the form of the function for STI and performance, and whether and to what extent the lowest STI-values differed from the higher values (STI 0.23, 0.34 and 0.71), with planned comparisons.

3.2 Word memory task

The analysis with acoustic condition as within-subjects factor revealed a significant effect of acoustic condition on performance (P [%]), F (5, 205) = 6.6, $p < 0.0001$, *partial* $\eta^2 = 0.14$. There was a significant linear trend when taking unequal spacing between the acoustic conditions into account, F (1, 41) = 23.5, $p < 0.001$, *partial* $\eta^2 = 0.36$; and with a tendency towards a significant cubic trend, F (1, 41) = 3.5, $p < 0.07$, *partial* $\eta^2 = 0.08$ (see Figure 5). The paired-comparisons (planned, one-tailed) showed that performances in the acoustic conditions from STI 0.00 to 0.23 were significantly different from those in STI 0.34 to 0.71 (see Table 2). There was no significant difference between STI 0.00 and 0.23. The major reduction in word memory performance takes place from STI 0.23 to 0.34, which supports the results from the first general analysis with all tasks grouped together (Figure 5). There was no significant difference between STI 0.71 and 0.34 which confirm that the ultimate performance drop is achieved at much lower STI values than Hongisto [1] suggests. Further, the performance decreased with about 5 % from baseline (STI 0.00) to the most critical STI-value for performance (i.e. STI 0.34).

3.3 Math task

The analysis with acoustic condition as the within-subjects factor revealed a significant effect of acoustic condition on performance (P [%]), F (5, 205) = 2.5, $p < 0.05$, *partial* $\eta^2 = 0.06$. This effect had a significant cubic trend when taking unequal spacing into account, F (1, 41) = 8.8, $p < 0.01$, *partial* $\eta^2 = 0.18$; but no significant linear trend F (1, 41) = 1.5, $p > 0.05$, *partial* $\eta^2 = 0.04$ (see Figure 5). The paired-comparisons showed that performance in the acoustic conditions 0.08, 0.16, and 0.23 were not significantly different from each other (see Table 3). However, performance in all of them was significantly better than in STI 0.34, where the worst performance was reached. The performance in silence (STI 0.00) also tended to be better than

with STI 0.34. The performance difference between STI 0.71 and 0.34 was not statistically significant and one cannot, therefore, state that performance at STI 0.71 would be better than at STI 0.34 as the tendency of the curve might indicate. In the Math task the performance decrease was less than 3 % from baseline (STI 0.00) to the most critical STI-value for performance (i.e. STI 0.34).

3.4 Information search task

The analysis with acoustic condition as within-subjects factor revealed no significant effect of acoustic condition on performance (P [%]), F (5, 205) = 1.3, $p > 0.05$, *partial* η^2 = 0.03. However, there was a tendency for a linear trend when taking unequal spacing into account, F (1, 41) = 3.4, $p = 0.07$, *partial* η^2 = 0.08. As seen in Figure 5, performance tended to follow a linear reduction from STI 0.16 to STI 0.71. The paired-comparisons showed that the acoustic conditions 0.00, 0.08, 0.16 and 0.23 did not differ significantly from each other (see Table 4). The comparison revealed, however, that the participants´ performance was significantly poorer in STI 0.71 than in STI 0.00 and 0.16. The significant decrease in performance from STI 0.00 to STI 0.71 was about 6 %.

3.5 Word fluency tasks

There were no significant effects ($F < 1$ and $p > 0.05$) of acoustic condition on the two Word fluency tasks (semantic- and phonemic fluency).

4. Discussion

We addressed two issues in Hongisto´s [1] prediction model. First, we tested the general STI (Speech Transmission Index) - performance function for a variety of office tasks. Second, we investigated whether the average maximum performance decrement differed in magnitude between the office-tasks.

4.1 The general function of speech intelligibility and performance

We found a main effect of acoustic condition on task performance in accordance with Hongisto´s [1] model, in two out of five tasks. In a further task we also found a difference in performance between the highest and lowest STI condition. The average of these three tasks is presented in Figure 6, curve B. It can be compared to the curve of Figure 1, which also represents an average

result over tasks selected whereby a significant performance change was reported in the literature.

However, the general form of the STI-performance functions deviated somewhat from Hongisto´s model. The steepest slope of overall performance decrease was located between 0.23 and 0.34 and the difference between 0.34 and 0.71 was negligible. These results partly disclaim *Hypothesis 1,* as Hongisto's model suggests that the steep slope of performance deterioration flattens out later just above STI 0.50. Also, the type of function was different depending on which task was performed, which was not considered in the Hongisto's model. For instance, for the Math task performance seems to drop off first from STI 0.16. However, the spread of the scatter points in Hongisto´s model is wide and our results at STI 0.71 do not differ more from the model than the data point from the study by, e.g. Venetjoki et al. [13].

4.2 *The influence of task characteristics on the maximum performance decrement*

The STI-performance functions looked different for the Word memory task and the Math task. Because of this, we investigated the difference between acoustic conditions in more detail and sought to determine whether the magnitude of maximum performance decrement differed between task characteristics.

The higher STI-values (STI 0.23, 0.34 and 0.71) made a difference to task performance only in certain tasks. In the Word memory task, performance decreased about 5 % from baseline (STI 0.00) to the most critical STI-value for performance (i.e. STI 0.34). As the Word memory task places high demands on both encoding and retrieval processes in semantic short-term memory, the results are compatible with the interference-by-process view, according to which auditory distraction is a result of a conflict between similar processing of the sound and the focal task [9]. The more intelligible the background speech was, the greater the performance impairment in this semantic short-term memory task.

In the Math task, there was less than a 3 % decrease in performance from baseline to the most critical STI-value for performance (i.e. STI 0.34). This task, consisting of simple addition, was obviously not as vulnerable to varying levels of speech intelligibility, compared to the Word memory task.

In the Information search task participants performed significantly worse in STI 0.71 compared to STI 0.00 (silence), between which the decrease in performance was greater than 6 %. This is in line with a study by Haka et al. [14] which shows that some tasks (i.e. operation span and serial memory) are not impaired until STI gets higher than 0.50.

For the Word fluency tasks there were no significant differences between acoustic conditions. One explanation for the invulnerability of these tasks to distraction is that they are based on long-term memory retrieval and do not need encoding or rehearsal of a to-be remembered material. Studies have shown that division of attention at encoding reduces memory performance markedly, while division of attention at retrieval has almost no effect on memory performance [28]. This is in line with an alternative explanation of auditory distraction, which states that sounds interrupt cognitive processes due to attentional capture [29]. Therefore, tasks with high demands on the encoding processes may be more vulnerable to distractions from background speech.

In summary, we have support for Hypothesis 2, as the average performance decrement depended on task type. The Word memory task, based on semantic short-term memory, was most vulnerable to intelligible speech, while there was no effect on the tasks based on long-term memory retrieval. There are, however, other feasible explanations to why the tasks applied in the present study reacted differently to the acoustic conditions. For instance, the complexity of the tasks and the use of different individual strategies for solving the tasks may render the tasks differentially sensitive to disruption via the irrelevant speech.

4.3 Limitations

4.3.1 The variety of STI-values and tasks

One of the limitations of the present study is that we did not have measurement points between STI 0.34 and 0.71 since we expected that the strongest performance change takes place between 0.00 and 0.34, and 0.71 was just the reference condition with perfect speech intelligibility. The validity of this assumption should be questioned and put to test in future studies.

It is likely that participants use more effort in high STI levels to maintain their performance [15]. However, self-rated effort or subjective workload was not measured in this study and we cannot say whether there was a balance between performance and effort over all STI levels and tasks. However, it is possible that the participants used more energy/resources to maintain their performance level in laboratory experiments because they are under continuous surveillance.

There is a need to explore a greater variety of tasks and discover a way to categorize them in terms of the mechanisms or processes they involve. One suggestion is to vary the tasks according to a given dimension (e.g. demands on rapidity or memory load) and investigate their differentially susceptibility to irrelevant speech. It is noted that there is a limitation in the

possibility of generalizing the results of the present study to other tasks, since the STI – performance function seems to differ significantly between tasks.

4.3.2 Uncertainties in the acoustic conditions

The original aim was that the acoustic conditions would not overlap. As described in the Method section, the STI value of individual sentences within a specific acoustic condition changed significantly because the sentences were not fully balanced in respect with speech spectrum. The outcome was that the STI of some sentences in the acoustic condition STI 0.16 overlapped with the standard range of the acoustic condition STI 0.23 (Figure 2). Therefore, the acoustic conditions STI 0.16 and 0.23 were perhaps not sufficiently different from each other. This may have reduced our possibilities to make clear discrimination of task performance in the STI range between 0.08 and 0.34. In future studies, it is suggested that the difference of nearby STI levels should not be less than 0.10.

Another question concerning the acoustic conditions is the uncertainty related with headphone listening. In this study, special care was taken that the headphone levels were correctly calibrated. However, the sound field produced to the ear channel depends strongly on the individual fitting of headphones. We tried to address this by giving the participants specific instructions on how to put them on before the experiment started. The within-participant design also assured the same circumstances between acoustic conditions. Changing to listening tests with loudspeakers and individual testing was not an alternative, since it would have been more time consuming.

One reason why the greatest performance loss was achieved already at STI 0.34 and not above 0.50, as suggested by Figure 1, might be that the content of sentences was very simple. In addition, the four-word sentences were very well pronounced. The sentence intelligibility of normal speech containing longer sentences (i.e. unpredictable content) and casual pronouncing is less intelligible. Therefore, we suggest that the subjective intelligibility associated with the reported STI values is higher than would be achieved with normal speech having the same speech-to-noise ratio. If this is indeed the case, the effects of low intelligible speech on performance may have been overestimated. Further, the original speech material was limited and the same sentences were used repeatedly, although randomly. The structure of each four-word sentence was also constant. These predictable syntactical structures may have helped the subjects to habituate to the acoustic stimulus [30]. It is also possible that the results would have been different if the speech was not so monotonic.

4.4 Practical implications of the study

The present study design is unique since it is one of the first experimental studies that contains several levels of speech intelligibility in the STI range where the largest change of performance was expected to occur according to the model of Hongisto [1]. Evidence from the field [4] and laboratory measurements [31, 32] show that it is possible to design the open-plan office in such a way that an STI below 0.50 is possible to achieve in a nearby workstation (2.5 m), or, at the least, in the second nearest workstation (5 m), with proper room acoustic design. Proper room acoustic design requires that sufficient absorption, high screens and appropriate speech masking is used.

The speech masking levels used in this study should not be used as guidelines for designing open-plan offices. Quite high masking sound levels, up to 51 dB (L_{Aeq}), were used to create the lowest STI values. The focus in this study was to give scientific support for the STI – performance function and specify the model for a variety of tasks. Suggested masking levels for open-plan offices range between 40 and 45 dB (L_{Aeq}) [20, 33].

The present results also imply that demands on tasks involving short term memory are more affected by irrelevant background speech than tasks that can rely on retrieval of information from long-term memory. This should be taken into account when designing the office. Workers doing mainly simple tasks may be less distracted by the irrelevant speech of an open-plan office than those doing demanding memory tasks. Similarly, better room acoustic designs, quiet open-plan office areas or private rooms are required for the optimal performance of more demanding tasks. In practice, this logic has already been tested in some offices [33] and this study yields support for the idea that better room acoustics in critical task areas might solve some problems in employee satisfaction and productivity.

4.5 Future research needs

The present analysis and results can serve as a platform for further investigations of the Hongisto´s [1] model of the STI - performance function. There is, for example, a need to sort out the details of the shape of the curve and the amount of performance decrement with more STI-values and tasks that, for example, can be classified with regard to semantic content, complexity and memory demands. Studies are also required that can rule out whether semantic or changing-state effects (e.g., attributable to the acoustic variability of the speech signal) explain the STI-performance function by including a control condition with meaningless speech.

It has been suggested that the STI of speech can be used to describe the disruptive potency of speech only in such conditions where the masking sound does not have temporal variations [20]. In this study, the masking sound was filtered pink noise and free from temporal variations. If the masking sound varies with time, like babble or other fluctuating sounds, STI may no longer fully explain the phenomenon observed here. However, the most typical masking sounds in open-plan offices are ventilation or road traffic sounds. In the future, studies containing time-varying maskers should be undertaken as there is evidence that fluctuating sounds are much more effective speech maskers than constant sounds [20].

5. Conclusions

This study aimed to clarify the model of Hongisto [1] describing the dependence of the performance decrement of cognitive tasks on the STI (Speech Transmission Index) of irrelevant speech. This study examined the effect of five different STI levels on the performance of five cognitively different tasks. The most important outcome was that the maximum performance decrease was already achieved at STI 0.34 with two out of five tasks while Hongisto [1] suggested that it is not achieved until STI exceeds 0.50. A maximum performance decrement above STI 0.50, suggested by Hongisto, was observed only with one task. Two tasks were not at all affected by speech. Attempts to reduce the STI in open-plan offices by way of altering room acoustics are strongly recommended if the cognitive work requires concentration and high short-term memory load. The target value of STI should be less than 0.50 between the speaker and the listener. In addition, the positive effect of acoustic design on work performance depends on the task type (i.e., the cognitive processes that underpin the task).

Acknowledgements

The international research cooperation between the authors of this article has received funding from the European Union's Seventh Framework Programme ([FP7/2007-2013]) under grant agreement n°226442. We would like to thank Staffan Hygge, John Marsh, Anders Kjellberg and Patrik Sörqvist for helpful comments on earlier drafts of this paper. For the first author the research was conducted in partial fulfilment of the requirements for a doctoral degree. This research was partly funded by AFA Insurance; the University of Gävle (Sweden) and Finnish Institute of Occupational Health. The work of the Finnish Institute of Occupational Health was a part of the TOTI project (User oriented office spaces) which was funded by Tekes and 10 companies.

Address for correspondence:

Ms. Helena Jahncke, Environmental Psychology, Faculty of Engineering and Sustainable Development, University of Gävle, SE-801 76 Gävle, Sweden

E-mail: helena.jahncke@hig.se

References

[1] V. Hongisto, A model predicting the effect of speech of varying intelligibility on work performance, Indoor Air. 15 (2005) 458-468.

[2] H. Jahncke, S. Hygge, N. Halin, A-M Green, K. Dimberg, Open-plan office noise: Cognitive performance and restoration, Journal of Environmental Psychology. 31(2011) 373-382.

[3] A. Kaarlela-Tuomaala, R. Helenius, E. Keskinen, V. Hongisto, Effects of acoustic environment on work in private office rooms and open-plan offices - longitudinal study during relocation, Ergonomics. 52 (2009) 1423-1444.

[4] P. Virjonen, J. Keränen, V. Hongisto, Determination of acoustical conditions in open-plan offices - Proposal for new measurement method and target values. Acta Acustica united with Acustica. 95 (2009) 279-290.

[5] J.E. Marsh, R.W. Hughes, D.M. Jones, Auditory distraction in semantic memory: A process-based approach, Journal of Memory & Language. 58 (2008) 682-700.

[6] N. Perham, J.E. Marsh, D.M. Jones, Syntax and serial recall: How language supports short-term memory for order. Q J Exp Psychol. 62 (2009) 1285-91.

[7] D.M. Jones, W.J. Macken, Irrelevant tones produce an irrelevant speech effect: Implications for phonological coding in working memory. Journal of Experimental Psychology: Learning, Memory, and Cognition. 19 (1993) 369-381.

[8] D.M. Jones, N. Morris, Irrelevant speech and serial recall: Implications for theories of attention and working memory, Scandinavian Journal of Psychology. 33 (1992) 212-229.

[9] J.E. Marsh, D.M. Jones, Cross-modal distraction by background speech: what role for meaning?, Noise and Health. 12 (2010) 210-216.

[10] IEC 60268-16:2003, Sound system equipment — Part 16: Objective rating of speech intelligibility by speech transmission index. International Organization for Standardization, Genève, Switzerland.

[11] V. Hongisto, A. Haapakangas, M. Haka, Task performance and speech intelligibility - a model to promote noise control actions in open offices, 9th International Congress on Noise as a Public Health Problem (ICBEN) July 21-25 (2008), 418-425. Mashantucket, Connecticut, USA.

[12] W. Ellermeier, J. Hellbrück, Is level irrelevant in irrelevant speech? Effects of loudness, signal-to-noise ratio, and binaural unmasking, J Exp Psychol Hum Percept Perform. 24 (1998) 1406-1414.

[13] N. Venetjoki, A. Kaarlela-Tuomaala, E. Keskinen, V. Hongisto, The effect of speech and speech intelligibility on task performance, Ergonomics. 49 (2006) 1068-1091.

[14] M. Haka, A. Haapakangas, J. Keränen, J. Hakala, E. Keskinen, V. Hongisto, Performance effects and subjective disturbance of speech in acoustically different office types - a laboratory experiment, Indoor Air, 19 (2009) 454-467.

[15] S. Schlittmeier, J. Hellbrück, R. Thaden, M. Vorländer, The impact of background speech varying in intelligibility: Effects on cognitive performance and perceived disturbance, Ergonomics. 51 (2008) 719-736.

[16] ISO 3382-3:2012. Acoustics — Measurement of room acoustic parameters — Part 3: Open-plan offices, International Organization for Standardization, Genève, Switzerland.

[17] FiSIAQ 2008, Classification of indoor climate. Finnish Society of Indoor Air Quality and Climate, Espoo, Finland. (Available in English).

[18] Swedish Standard, designation SS-EN 12464-1. Ljus och belysning - Belysning av arbetsplatser - Del 1: Arbetsplatsens utformning [*Light and lighting - Lighting of work places - Part 1: Workplace Design*]. ICS code 91.160.10; 2003.

[19] B. Hagerman, Sentences for testing speech intelligibility in noise, Scandinavian Audiology. 11 (1982) 79-87.

[20] A. Haapakangas, E. Kankkunen, V. Hongisto, P. Virjonen, D. Oliva, E. Keskinen, Effects of five speech masking sounds on performance and acoustic satisfaction - implications for open-plan offices, Acta Acustica united with Acustica. 97(2011) 641-655.

[21] P. Larm, V. Hongisto. Experimental comparison between speech transmission index, rapid speech transmission index, and speech intelligibility index, Journal of the Acoustical Society of America. 119 (2006) 1106-1117.

[22] T. Houtgast, H.J.M. Steeneken, A review of the MTF concept in room acoustics and its use for estimating speech intelligibility in auditoria. Journal of Acoustic Society of America, 77 (1985) 1069–1077.

[23] H. Jahncke, N. Halin, Performance, fatigue and stress in open-plan offices: the effects of noise and restoration on hearing impaired and normal hearing individuals, Noise & Health. (Accepted).

[24] A.J. Fürst, G.J. Hitch, Separate roles for executive and phonological components of working memory in mental arithmetic, Memory & Cognition. 28 (2000) 774-782.

[25] A.K. Troyer, M. Moscovitch, G. Winocur, M.P. Alexander, D. Stuss, Clustering and switching on verbal fluency: the effects of focal frontal- and temporal-lobe lesions, Neuropsychologia. 36 (1998) 499-504.

[26] J.P. van Overschelde, K.A. Rawson, J. Dunlosky. Category norms: an updated and expanded version of the Battig and Montague (1969) norms, Journal of Memory and Language. 50 (2004) 289-335.

[27] J.G. Borkowski, A.L. Benton, O. Spreen, Word fluency and brain damage, Neuropsychologia. 5 (1967) 135-140.

[28] M. Naveh-Benjamin, F.I.M. Craik, J.G. Perretta, S.T. Tonev, The effects of divided attention on encoding and retrieval processes: the resiliency of retrieval processes, The Quarterly Journal of Experimental Psychology. 53 (2000) 609-625.

[29] N. Cowan, Attention and memory: An integrated framework. Oxford University Press, Oxford, 1995.

[30] P. Sörqvist, A. Nöstl, N. Halin, Working memory capacity modulates habituation rate: Evidence from a cross-modal auditory distraction paradigm, Psychon Bull Rev. 19 (2012) 245–250.

[31] J. Keränen, V. Hongisto, J. Hakala, D. Oliva, Speech privacy in an open-plan office with different room acoustic conditions, Forum Acusticum, paper 135, 1897-1900, 27 June - 1 July (2011), Aalborg, Denmark.

[32] P. Virjonen, J. Keränen, R. Helenius, J. Hakala, V. Hongisto, Speech privacy between neighbouring workstations in an open office - a laboratory study, Acta Acustica united with Acustica. 93 (2007) 771-782.

[33] V. Hongisto, A. Haapakangas, R. Helenius, J. Keränen, D. Oliva, Acoustic satisfaction in an open-plan office before and after the renovation, Proceedings of Euronoise 2012, 654-659, June 10-13, Prague.

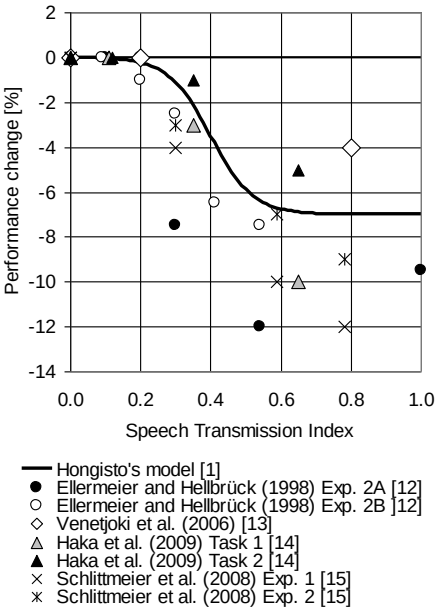


Figure 1. The schematic prediction model which gives the change of performance as a function of the STI (modified from Hongisto et al., 2008). Normal performance is obtained when no speech is heard (STI = 0.00), as between nearby office rooms. The highest performance decrease is reached when speech is highly intelligible (STI > 0.70), as between nearby workstations in an open-plan office with poor acoustic privacy.

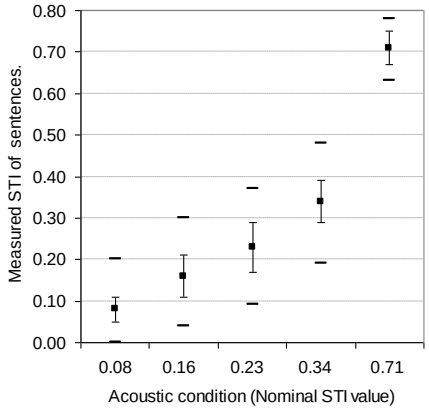


Figure 2. The statistical distribution of STI of individual sentences in the acoustic conditions containing speech. Square: average. Whiskers: standard deviation (67 %). Bars: minimum and maximum values.

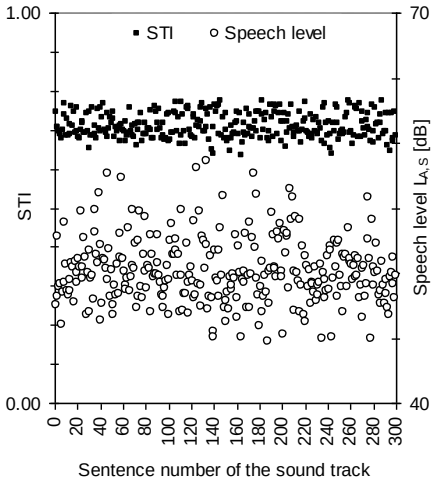


Figure 3. A typical example of the variation of the STI and speech level of individual sentences in sound tracks. In this example, the mean STI was 0.71 and the mean speech level was 51 dB (LAeq).

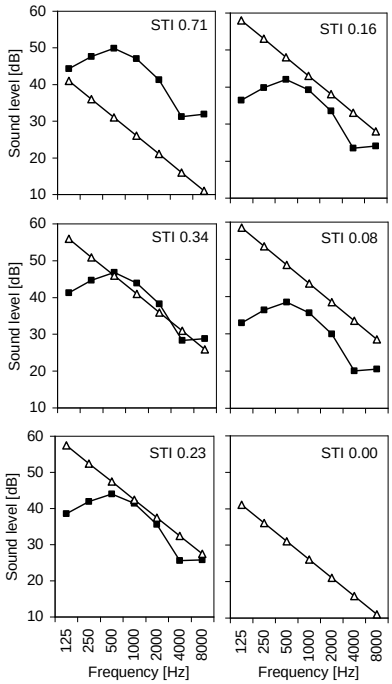


Figure 4. The linear time-averaged sound pressure levels of speech (black square) and masking sound (hollow triangle) in the six acoustic conditions at octave bands. These values were used to determine the average STI values.

Figure 5.

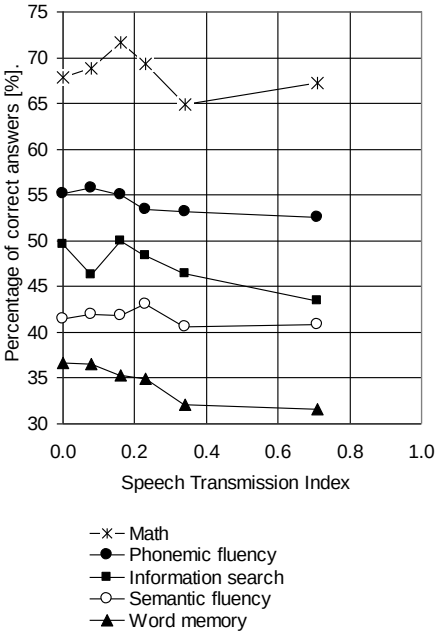


Figure 5. The STI – performance function for the five cognitive tasks.

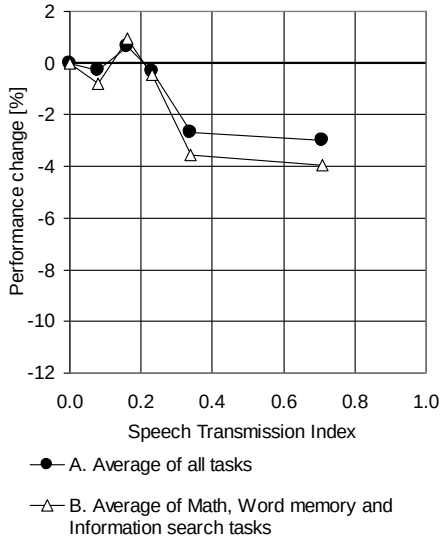


Figure 6. Task-averaged performance change between acoustic conditions. Curve B is comparable with the model of Figure 1 since it contains only the tasks where there was a significant difference in performance between acoustic conditions.

Table 1. The description of the six acoustic conditions. The names of the acoustic conditions represent also their measured time-averaged STI values. $L_{A,S}$ = A-weighted level of speech, $L_{A,M}$ = A-weighted level of masking sound, and $L_{A,tot}$ = A-weighted level of the sum of speech and masking. All levels are equivalent sound pressure levels.

Acoustic condition	$L_{A,S}$ [dB]	$L_{A,M}$ [dB]	$L_{A,tot}$ [dB]
0.00		33.0	33.0
0.08	39.6	50.7	51.0
0.16	43.2	50.2	51.0
0.23	45.3	49.6	51.0
0.34	47.9	48.1	51.0
0.71	51.0	33.2	51.1

Table 2. The t-test comparisons (t-values, one-tailed) of performance between the acoustic conditions in the Word memory task. Asterisks describe the statistical significance level of the difference between the STI values. The t-values for the planned comparisons are bolded.

Acoustic condition	0.08	0.16	0.23	0.34	0.71
0.00	0.1	1.2	**1.5**	**3.9*** **	**4.3*** **
0.08		1.1	**1.3**	**4.1*** **	**3.6*** **
0.16			**0.3**	**2.7** **	**3.3*** **
0.23				**2.5** **	**2.4** **
0.34					**0.5**
0.71					

Note: ** p<.01, *** p<.001

Table 3. The t-test comparisons (t-values, one-tailed) of performance between the acoustic conditions in the Math task. Asterisks describe the statistical significance level of the difference between the STI values. The t-values for the planned comparisons are bolded.

Acoustic condition	0.08	0.16	0.23	0.34	0.71
0.00	-0.5	-2.0*	**-0.8**	**1.5**	**0.3**
0.08		-1.4	**-0.3**	**2.0***	**0.7**
0.16			**1.9**	**3.3*****	**2.1***
0.23				**2.7****	**0.9**
0.34					**-1.2**
0.71					

Note: * p<.05, ** p<.01, *** p<.001

Table 4. The t-test comparisons (one-tailed) of performance between the acoustic conditions in the Information search task. Asterisks describe the statistical significance level of the difference between the STI values. The t-values for the planned comparisons are bolded.

Acoustic condition	0.08	0.16	0.23	0.34	0.71
0.00	1.2	-0.1	**0.4**	**0.9**	**2.2***
0.08		-1.4	**-0.8**	**-0.1**	**0.8**
0.16			**0.6**	**1.0**	**1.8***
0.23				**0.6**	**1.6**
0.34					**0.9**
0.71					

Note: * p<.05

Paper IV

Open-plan office noise: The susceptibility and suitability of different cognitive tasks for work in the presence of irrelevant speech

Helena Jahncke[1]

[1] *Environmental Psychology, Faculty of Engineering and Sustainable Development, University of Gävle, SE-801 76 Gävle, Sweden*

Submission Date: 24-2-2012
Review completed: 19-6-2012
Accepted Date: 13-8-2012
Technical editing: 17-8-2012
Copyediting: 17-8-2012

Abstract

The aim of the present study was to test which tasks are suitable for work in open-plan offices according to how susceptible they are to disruption produced by the mere presence of irrelevant speech. The tasks were chosen to tap fundamental capacities of office work involving: search for relevant information, remembering material, counting, and generation of words. The hypothesis was that tasks requiring semantic processing should be impaired by irrelevant speech. To determine the magnitude of performance decrease, two sound conditions (quiet, irrelevant speech) were compared. The results showed that tasks based on episodic short-term-memory and rehearsal of the presented material was more sensitive to disruption by irrelevant speech than tasks which did not require rehearsal or were based on long-term memory retrieval. The present study points to the inappropriateness of tasks, such as information search and remembering of material, for work environments within which irrelevant speech is ubiquitous.

Key Words: Long-term memory, Noise, Semantic auditory distraction, Working memory

Introduction

There is a widespread concern for how undesired sounds in offices affect cognition and performance. [1,2] Many noise sources are potentially disruptive; however, several studies have shown that irrelevant speech from colleagues is the most troublesome, especially for performance and perceived disturbance in open-plan offices.[3] In addition, there are studies which indicate that some tasks are more affected by irrelevant speech than others.[4,5] The aim of this study is to further specify which tasks are more – as compared to less – sensitive to

disruption via irrelevant speech. This may give an indication of which tasks are suitable or inappropriate to work with in open-plan offices as these designs promote noisy work environments.

Several studies have shown that reading comprehension,[6,7] information search,[5] recall of previously presented semantic information[8,9] and writing processes,[10] which all require semantic processing (i.e., processing of meaning), are detrimentally affected by irrelevant speech. This outcome is commonly explained as a cognitive conflict between the automatic semantic processing of irrelevant background speech and the simultaneous semantic processing of those tasks.[11,12] Support for the automatic semantic processing of speech sounds, even if the sound is unattended, comes from both neuroscientific[13] and behavioral[14] studies.

However, if a task only involves rehearsal of information in a specific order (e.g. recall of the digits in a telephone number) rather than semantic processes, other properties of the sound (i.e. sound that changes in terms of frequency or pitch) have been shown to be more disruptive than the semantic aspects of sound. In this case a processing conflict occurs when the order of events in the sound and of the focal task are simultaneously processed, which is called *the irrelevant sound effect*.[15] Perham, Banbury, and Jones[16] have shown that retrieval instructions can influence the extent to which rehearsal is adopted and consequently the degree of disruption. Therefore, the mere presence of sound (e.g. irrelevant speech) can impair performance in tasks that require serial processing or where the most efficient strategy is rehearsal, as long as the sound changes across time. It has also been shown that counting, a fundamental work task for several professions, is impaired by irrelevant sounds, but this occurs regardless of whether the background noise consists of speech numbers.[17] Even if counting does require some processing of meaning, these results suggest there are few demands on semantic processing when the math task is simple.

Jahncke, Hongisto and Virjonen[5] have tested the magnitude of disruption by irrelevant speech on a variety of cognitive tasks. The results showed, for instance, that a word memory task was more impaired by speech with high levels of intelligibility than a math task was. However, as the two tasks contained different materials, it is difficult to tell whether it is the complexity, the difficulty level, or the cognitive processes that make tasks differ in sensitivity to disruption from irrelevant speech. Furthermore, Marsh and Jones[12] have investigated the effects of meaningful speech on one task with different semantic demands. They showed that a word generation task

with semantic retrieval (semantic fluency, such as generating members of a specific semantic category) was disrupted by meaningful background speech but phonemic retrieval (phonemic fluency, such as generating words that all begin with the same phoneme) was not. Moreover, the disruption increased when the background speech was semantically related to the semantic fluency task (e.g., when the spoken words were members of the same semantic category as the to-be-retrieved words). The main focus in the present study is to test which tasks (the components of which are relevant to office work), are more or less susceptible to disruption from background speech. The first hypothesis is that performance in tasks based on semantic processing (e.g. word memory, semantic fluency and information search) will be more impaired by irrelevant background speech than tasks based on other or less semantic cognitive processes (e.g. counting and phonemic fluency). A related aim is to test whether changes in types of processing demands modulate the task's sensitivity to disruption from irrelevant speech. For this purpose, a novel task (word memory: category- and structural word finding; further described under method section) was developed, which changes the requirements of semantic processing by varying the processing instruction (i.e., changing the mental operations that participants perform on the to-be-remembered material), without changing the test material per se. Research on incidental learning has, for instance, shown that manipulating instructions in this way indeed changed the processing requirements.[18] More specifically, the second hypothesis is that performance in the novel task will be more impaired when the participants are following the semantic instruction compared to the structural instruction.

Method

Participants

The experiment was carried out in sound proof rooms. A total of 24 persons recruited from the University (mean age = 25; 8 females) took part in the study in exchange for two cinema tickets. All participants reported their hearing and vision to be normal.

Noise conditions

Two noise conditions were compared: quiet versus irrelevant speech. The speech was presented by individual laptops and headphones. The irrelevant speech was played back at an average level of 51 dB (A), which is a typical overall level in open-plan offices.[3] The quiet condition was approximately 30 dB (A).

The original speech was recorded in an anechoic room and should not be overvalued as a realistic office noise. However, the irrelevant speech conveyed meaningful information and

consisted of 120 different sentences spoken by a female actress and 120 different sentences spoken by a male actor, thus yielding 240 sentences. Each sentence had simple semantic content, e.g. "Japanese cars are cheap." The duration of each sentence was three seconds. The sentences were spoken in Swedish with clear articulation. The sentences were looped in random order during the experimental session.

Cognitive measures

Memory: category- and structural word finding

The aim in relation to these tasks was to manipulate the cognitive processes involved while performing the tasks. Therefore, two versions of the instructions were used but the material was kept the same (i.e. lists of words). In both cases three lists with ten words each were presented before the participants had to recall the words in free order. In the first version of the memory task the participants were instructed to remember all words within a named category (e.g. a toy) while searching lists of words. This part of the task was intended to measure memory for semantic targets. In the second version of the memory task the participants were instructed to remember words beginning with a certain letter. This version of the task was intended to measure memory for structural targets. Even if these tasks are based on either semantic or structural analysis of the targets, both tasks put high demands on episodic memory and presumably rehearsal of the to-be-remembered material. Both versions of the task are relevant to office work because they tap processes required to search through material and memorize relevant parts. The words were only included once (i.e. never repeated) to avoid recognition or interference with earlier presented words. Each list with words (shown in rows) was visible for 6 seconds. There were ten trials (in total 30 lists) for each sound condition and task. For each trial (three lists) six words were correct. The correct words were divided between the lists in two ways. In every second trial there were two correct words per list and in the other half, there were one correct word in the first list, three correct words in the second list, and two correct words in the last list.

For the category memory task, the same numbers of categories were selected to both versions of the task according to Overschelde, Rawson and Dunlosky´s[19] difficulty level rankings. The following categories were included within one of the versions: a unit of time, a type of footwear, a tree, a weapon, a type of dance, a type of reading material, a type of fabric, a toy, a flower and a herb. In the other version the following categories were included: a sport, a vegetable, a substance for flavoring food, an alcoholic beverage, a type of human dwelling, a thing that flies,

a liquid, a carpenter´s tool, a thing that is green and a part of speech. The two versions were counter balanced between participants over the two sound conditions.

For the structural memory task the participants were instructed to remember words beginning with the following Swedish letters in one version of the task*: H, N, A, V, O, J, T, Ä* and *L;* and in the other version*: E, Å, M, R, Ö, I, Y, P, U* and K. The two versions were counter balanced between participants over the two sound conditions.

Word generation: semantic- and phonemic fluency

Two versions of the word generation task[20] were developed by Jahncke *et al.*,[5] and adopted in the present study to test semantic- and phonemic fluency. The procedure for the Semantic fluency task was that the participants were given 60 seconds to generate (write) as many exemplars from a given semantic category as possible. Directly after the first category, another category was presented with the same time limit. Jahncke *et al.*,[5] used the updated and expanded version of Battig and Montague category norms developed by Overschelde, Rawson and Dunlosky[19] for category selection, to keep the difficulty level fairly constant between the versions of the task. The categories were: a four-footed animal, a thing that makes noise, a musical instrument and a kitchen utensil. The scores were the sum of correctly generated words and the task took two minutes to perform (i.e. two categories).

In the Phonemic fluency task the participants were presented with a letter and told to generate as many words as possible during 60 seconds that begin with the given letter. However, they were not allowed to generate variants of the same word: e.g., sail, sailing, and they were instructed to avoid producing proper nouns (e.g. names of places, people and products). Jahncke *et al.*.[5] based the letter selection to the phonemic fluency task on the study by Borkowski, Benton and Spreen,[21] which defined the difficulty level of the letters according to the associated word frequency. In each of the six versions of the task two letters were presented. One letter were taken from the easy range category of difficulty (i.e. H, D, M, A, B, F) and one from the moderate range category (i.e. O, N, E, G, L, R), to keep the difficulty level fairly constant between the versions of the task. The scores were the sum of correctly generated words and the task was given two minutes to perform. Both of the fluency tasks require retrieval from long-term memory, with either a semantic or phonemic activation of words. These tasks do not involve rehearsal of a to-be-remembered material and are relevant to office work in the respect that they tap processes to generate written texts and ideas.

Information search task

The information search task was adopted from Jahncke and Halin.[22] This task was originally designed to have relevance for office work because it taps key processes required to search through and comprehend the contents of a table of information, while successively updating and memorizing which information is most correct according to a target criterion. This task is therefore based on episodic memory and rehearsal and updating of the to-be-remembered material.

In the task seven columns of information were given about price, location, area, year etc. The twenty rows kept together the information about a given object (e.g., a person, a house or a country). The participants were asked to find the object that met a set of criteria, by using three columns. Each experimental block consisted of twelve questions and the time was limited to one minute per question before a new question was presented. The scores were the sum of correct answers and the average answer time. The task took 12 minutes to perform.

Math task

This task was an addition task where participants were instructed to add triple-digit numbers (e.g. 146+309).[5] This task was included as arithmetic is relevant to office work, especially for economists, engineers etc. Each experimental block consisted of 25 pairs of triple-digit expressions presented one by one together with an answer box. Every second expression had two carry over operations and the others had one carry over operation. Fürst and Hitch[23] have argued that this carrying component in mental arithmetic puts high demands on inhibition and memory processes of interim results in working memory. This task therefore require some kind of episodic or working memory (i.e. storage of a solution), though presumably with less episodic demands than the word memory tasks and fewer semantic demands than the fluency tasks. In each of the six versions of this task there were different numbers to sum up. The answer time was set to 18 seconds per expression. The scores were the sum of correct answers and the average answer time. The task took approximately 7 minutes to perform.

Design

The hypotheses were tested by using a within-person design with two noise conditions (quiet; irrelevant background speech) and four different tasks expected to involve diverse cognitive processes (word generation; memory from semantic-/structural word finding; counting; and information searching).

Procedure

Data collection took place in sound proof rooms. The participants sat in isolation and worked with the cognitive tasks on a laptop and they had headphones on during the whole session. First the participants undertook a short practice session of all tasks in quiet. Then they proceeded through the other tasks and noise conditions in random order. The following restrictions for the randomization were used: the same task was not allowed to be performed in noise and quiet directly after each other; and a maximum of three tasks with the same noise condition were allowed to be presented in a row. In this manner each participant performed all of the tasks during both quiet and noise but in a random order. The session took about one hour to complete.

Results

The analysis revealed a main effect of background speech on information search, $F(1, 23) = 9.47$, $p < 0.005$, *partial* $\eta^2 = 0.29$; on memory from category word finding, $F(1, 22) = 7.12$, $p < 0.02$, *partial* $\eta^2 = 0.25$; and on memory from structural word finding, $F(1, 23) = 14.14$, $p < 0.001$, *partial* $\eta^2 = 0.38$; indicating lower performance with background speech compared to quiet in line with the hypothesis [Figure 1]. More specific, performance decreased from quiet to background speech with 8.7% for the information search, 6.5% for memory from category word finding, and 10.6 % for memory from structural word finding.

Further, in line with the hypothesis there was no effect of background speech on math performance, $F(1, 23) = 0.17$, $p = 0.68$, *partial* $\eta^2 = 0.01$; and on phonemic fluency, $F(1, 23) = 1.06$, $p = 0.31$, *partial* $\eta^2 = 0.04$. Unexpectedly there was no effect of background speech on semantic fluency, $F(1, 23) = 0.26$, $p = 0.62$, *partial* $\eta^2 = 0.01$. Performance decreased from quiet to background speech with 3.3% for math, 4.2% for phonemic fluency and 2.4% for semantic fluency. No effects of background speech were found on answer time in the information search and math task.

(Please, insert Figure 1 about here.)

Discussion

This experimental study addressed the issue of which tasks (the components of which are relevant to office work), are more or less susceptible to disruption by the mere presence of irrelevant speech.

The main findings are that the information search task and the two memory based tasks (structural- and category words finding) were affected by irrelevant speech, but the math task and the two fluency tasks (semantic- and phonemic fluency) were not. This was not entirely expected as it was hypothesized that the semantic fluency task would be sensitive to irrelevant speech because of the requirements of semantic processing and the presence of semantic information in the irrelevant speech. Furthermore, it was hypothesized that the structural-memory task would be resistant to background speech as it arguably does not involve semantic processing.

First, to understand why both of the memory based tasks were impaired by background speech, and neither of the two fluency tasks, it is important to note their differences in the functional attributes of these tasks. The two memory tasks were based on episodic memory and presumably rehearsal of the to-be-remembered material which is the main strategy for keeping information available for report, and hence, should make the tasks susceptible to disruption from changing-state characteristics of the sound. In contrast, the fluency tasks required retrieval of words from long-term memory and were accordingly not based on rehearsal of a to-be-remembered material. Jones, Marsh and Hughes[24] argued in a recent study that different stages of a task (i.e. encoding, rehearsal and retrieval) can be impaired by irrelevant speech. They showed that semantic fluency, which is based on retrieval, is only vulnerable to speech if the speech is meaningful; and is even more impaired if the speech is related semantically to the retrieval category. However, meaningful speech was used in the current experimental study and semantic fluency appeared invulnerable to disruption. Although speculative, the difference between Jones *et al.*,[24] and the current findings may depend on the level of abstractness of the categories selected, the size of those categories, or on the semantic properties of the background speech. This clearly needs to be subject of further investigation.

The remaining results may also be explained within the perspective of different memory processes and stages. Another variable of interest is the presence of visual supports which will require different levels of rehearsal. Tasks were presented visually, but some provided timed

presentations while others maintained more visual support. Indeed with full visual support in timetable-type tasks, the disruptive effect of irrelevant speech is eliminated.[25] In the context of the information search task used in the current study, episodic memory and rehearsal is necessary because the task required the participants to search through a table of information whilst remembering (and updating) which target was closest to the given statement. This use of rehearsal presumably made the task vulnerable to disruption via background speech. The math task, on the other hand, only included a simple addition of numbers, and perhaps did not require as much by way of rehearsal as each operation was visible during the whole answer time and the answer did not need to be memorized or updated, but could be written directly in the answer box. The low demands on rehearsal in the simple math task might therefore explain its resistance to any disruption produced by the background speech. The present results suggest that irrelevant speech produces poorer performance in tasks with high episodic memory and rehearsal demands (i.e. word memory and search task), but very little reduction in performance on tasks that make fewer demands on episodic memory processes (i.e. math), or those tasks based on long term memory (i.e. fluency task). This is in line with earlier studies showing that episodic memory tasks are more disrupted by noise than are semantic tasks[26] and that the retrieval strategy can influence the degree of disruption by noise[16] However, as these tasks are complex and there are different mnemonic properties (in terms of processes and content) involved across the tasks that have been compared, it is difficult to draw strong conclusions. Some of the limitations of this type of research stem not necessarily from flaws in design, but simply from the noteworthy attempt to describe the influences of distraction on completion of complex tasks.

Further, it can be questioned from another point of view why the two word memory tasks did not differ as hypothesized. The second hypothesis stated that performance should be more impaired when the participants were following the semantic instruction compared to the structural instruction. A plausible explanation is that the initial part of the tasks, requiring analysis of either semantic or structural targets, was not sensitive to irrelevant speech, though the following processes were (i.e. episodic memory and rehearsal). As both tasks required the latter processes no significant differences between the tasks was obvious.

However, it is important to note that the absence of meaningless irrelevant speech as a control condition potentially obscures identification of the variable(s) responsible for producing the irrelevant speech effect in the context of the word memory tasks: without a meaningless irrelevant speech condition, it cannot be ascertained whether the tasks were impaired by the

changing acoustical properties of the irrelevant sound such as in serial recall (in which one would expect no additional disruption from meaningful speech compared to meaningless speech), or whether the disruption was a semantic irrelevant sound effect (in which one would expect additional disruption from meaningful speech).[27] Also, Perham *et al.*,[25] indicated that minimizing the demands on rehearsal in a task made the irrelevant speech effect disappear, compared to when the demands on rehearsal were high.

Furthermore, the irrelevant speech was composed of randomly presented sentences – not discourse. While the sentences contained semantic information, they were not related to one another. Speech distraction in an office situation might be more discourse oriented (overheard conversations, etc.) and as such a comparison between the random sentences and connected discourse might be more meaningful than comparisons with meaningless speech and random sentences, if the purpose is to discuss effects on office performance. However, in this study we focused on random sentences as it can also be distracting to overhear half of a conversation (i.e. telephone calls from colleagues) where the heard sentences become more random for the listener.[28] As mentioned earlier, the present study did not aim at ruling out theoretical explanations of why background speech is disruptive. The main focus in this study was merely to explore which tasks are suitable to work with in open-plan offices where exposure to irrelevant speech sounds is frequent. The ecological validity of the tasks included can therefore be discussed. The tasks investigated were chosen to tap fundamental characteristics of office work, involving the search for relevant information, remembering material, counting, and generating words (which underpins language production). Further research is needed to investigate a greater variety of open-plan office settings (i.e. speech surroundings) and tasks with different attributes. As researchers, we are left with the difficult task of attempting to isolate components of tasks that are susceptible to distraction, whilst concluding as the cause of distraction on integrative tasks that embody more than one of the identified component processes. This becomes problematic when one wishes to make important recommendations about office environments based on the results. Functional and practical conclusions from this study are necessarily limited as a result.

In summary, some basic conclusions can be drawn. The automatic processing of irrelevant speech impedes the cognitive processes required to rehearse to-be-remembered material. According to the results of this study it appears that tasks which require episodic memory and the process of rehearsal—such as information searching and word memory—are better

performed during quiet. Word fluency (based on material stored in long-term-memory) and simple counting however, are less susceptible to disruption via the presence of irrelevant speech. Since work tasks differ in how vulnerable they are for background speech, it is important to consider which work environments are optimal for each kind of task component.

Acknowledgements

This research was funded by AFA Insurance and the University of Gävle and was conducted in partial fulfillment for the requirements for a doctoral degree. I would like to thank John Marsh, Patrik Sörqvist and Staffan Hygge for helpful comments on earlier drafts of this manuscript.

Address for correspondence:

Ms. Helena Jahncke, Environmental Psychology, Faculty of Engineering and Sustainable Development, University of Gävle, SE-801 76 Gävle, Sweden

E-mail: helena.jahncke@hig.se

References

1. Szalma JL, Hancock PA. Noise effects on human performance: A meta-analytic synthesis. Psychol Bull 2011;137:682-707.
2. Jahncke H, Hygge S, Halin N, Green AM, Dimberg K. Open-plan office noise: Cognitive performance and restoration. J Environ Psychol 2011;31:373-82.
3. Kaarlela-Tuomaala A, Helenius R, Keskinen E, Hongisto V. Effects of acoustic environment on work in private office rooms and open-plan offices - longitudinal study during relocation. Ergonomics 2009;52:1423-44.
4. Beaman CP, Jones DM. Role of serial order in the irrelevant speech effect: Tests of the changing-state hypothesis. J Exp Psychol Learn Mem Cogn 1997;23:459-71.
5. Jahncke H, Hongisto V, Virjonen P. Cognitive performance during irrelevant speech: Effects of speech intelligibility and semantic difficulty. Applied Acoustics 2012; Accepted.
6. Oswald CJP, Tremblay S, Jones DM. Disruption of comprehension by the meaning of irrelevant sound. Memory 2000;8:345-50.
7. Sörqvist P, Halin N, Hygge S. Individual differences in susceptibility to the effects of speech on reading comprehension. Appl Cogn Psychol 2010;24:67-76.
8. Bell R, Mund I, Buchner A. Disruption of short-term memory by distractor speech: Does content matter? Q J Exp Psychol (Hove) 2011;64:146-68.
9. Beaman CP. The irrelevant sound phenomenon revisited: What role for working memory capacity? J Exp Psychol Learn Mem Cogn 2004;30:1106-18.
10. Sörqvist P, Nöstl A, Halin N. Disruption of writing processes by the semanticity of background speech. Scand J Psychol 2012;53:97-102.
11. Marsh JE, Hughes RW, Jones DM. Auditory distraction in semantic memory: A process-based approach. J Mem Lang 2008;58:682-700.
12. Marsh JE, Jones DM. Cross-modal distraction by background speech: What role for meaning? Noise Health 2010;12:210-6.

13. Beaman CP, Bridges AM, Scott SK. From dichotic listening to the irrelevant sound effect: A behavioral and neuro imaging analysis of the processing of unattended speech. Cortex 2007;43:124-34.
14. Sörqvist P, Marsh JE, Jahncke H. Hemispheric asymmetries in auditory distraction. Brain Cogn 2010;74:79-87.
15. Perham N, Marsh JE, Jones DM. Syntax and serial recall: How language support short-term memory for order. Q J Exp Psychol 2009;62:1285-91.
16. Perham N, Banbury SP, Jones DM. Reduction in auditory distraction by retrieval strategy. Memory 2007;15:465-73.
17. Buchner A, Steffens MC, Irmen L, Wender KF. Irrelevant auditory material affects counting. J Exp Psychol Learn Mem Cogn 1998;24:48-67.
18. Shulman HG. Similarity effects in short-term memory. Psychol Bull 1971;75:399-415.
19. Van Overschelde JP, Rawson KA, Dunlosky J. Category norms: An updated and expanded version of the Battig and Montague (1969) norms. J Mem Lang 2004;50:289-335.
20. Troyer AK, Moscovitch M, Winocur G, Alexander MP, Stuss D. Clustering and switching on verbal fluency: The effects of focal frontal- and temporal-lobe lesions. Neuropsychologia 1998;36:499-504.
21. Borkowski JG, Benton AL, Spreen O. Word fluency and brain damage. Neuropsychologia 1967;5:135-40.
22. Jahncke H, Halin N. Performance, fatigue and stress in open-plan offices: The effects of noise and restoration on hearing impaired and normal hearing individuals. Noise & Health 2012; Accepted.
23. Fürst AJ, Hitch GJ. Separate roles for executive and phonological components of working memory in mental arithmetic. Mem Cognit 2000;28:774-82.
24. Jones DM, Marsh JE, Hughes RW. Retrieval from memory: Vulnerable or inviolable? J Exp Psychol Learn Mem Cogn 2012;38:905-22.
25. Perham N, Banbury S. The role of rehearsal in a novel call centre-type task. Noise Health 2012;14:1-5.
26. Boman E, Enmarker I, Hygge S. Relative strength of noise effects on memory processes in pupils and teachers depending on noise source and age. Noise Health 2005;7:11-26.
27. Marsh JE, Hughes RW, Jones DM. Interference by process, not content, determines semantic auditory distraction. Cognition 2009;110:23-38.
28. Monk A, Fellas E, Ley E. Hearing only one side of normal and mobile phone conversations. Behav Inf Technol 2004;23:301-5.

Source of Support: This research was funded by AFA Insurance and the University of Gävle.

Conflict of Interest: None declared.

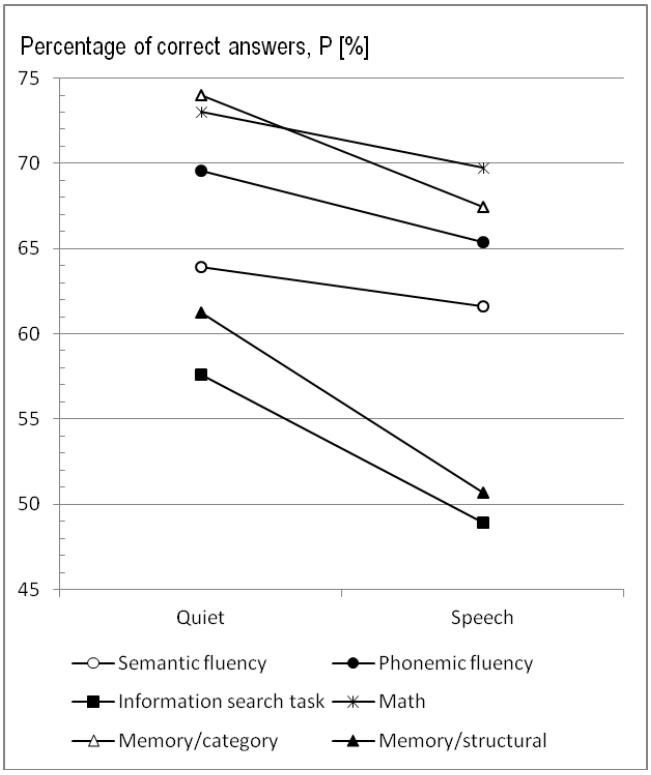


Figure 1: Percentage of correct answers in the cognitive tasks during quiet and irrelevant speech.