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The effect of noise absorption variation in open-plan offices: A field study with a cross-over design

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ABSTRACT

Noise has repeatedly been shown to be one of the most recurrent reasons for complaints in open-plan office environments. The aim of the present study was to investigate if enhanced or worsened sound absorption in open-plan offices is reflected in the employees' ratings of disturbances, cognitive stress, and professional efficacy. Employees working on two different floors of an office building were followed as three manipulations were made in room acoustics on each of the two floors by means of less or more absorbing tiles & wall absorbents. For one of the floors, the manipulations were from better to worse to better acoustical conditions, while for the other the manipulations were worse to better to worse. The acoustical effects of these manipulations were assessed according to the new ISO-standard (ISO-3382-3, 2012) for open-plan rooms acoustics. In addition, the employees responded to questionnaires after each change. Our analyses showed that within each floor enhanced acoustical conditions were associated with lower perceived disturbances and cognitive stress. There were no effects on professional efficiency. The results furthermore suggest that even a small deterioration in acoustical room properties measured according to the new ISO-standard for open-plan office acoustics has a negative impact on self-rated health and disturbances. This study supports previous studies demonstrating the importance of acoustics in work environments and shows that the measures suggested in the new ISO-standard can be used to adequately differentiate between better and worse room acoustics in open plan offices.

1. Introduction

In relation to other ambient factors, the impact of unwanted sound or noise is probably the most studied when it comes to office environments (Boyce, 1974; De Croon, Sluiter, Kuijer, & Frings-Dresen, 2005; Leather, Beale, & Sullivan, 2003; Leder, Newsham, Veitch, Mancini, & Charles, 2015; Navai & Veitch, 2003; Nemecek & Grandjean, 1973; Pejtersen, Allermann, Kristensen, & Poulsen, 2006; Sundstrom, Burt, & Kamp, 1980; Sundstrom, Town, Rice, Osborn, & Brill, 1994; Veitch, Charles, Farley, & Newsham, 2007; Veitch, Farley, & Newsham, 2002; Warnock, 2004). Noise has been suggested to cause interruption, irritation and lowered performance among employees (Roelofsen, 2008), and is one of the most common reasons for complaints in open-plan office environments (Kaarlela-Tuomaala, Helenius, Keskinen, & Hongisto, 2009). However, this study addresses something that is less known about noise, namely, how better or worse acoustical conditions in open-plan offices affect employees' perception of disturbances, cognitive stress, and professional efficacy.

Why noise is a common reason for complaints can be explained by the *changing state hypothesis* (Jones, Madden, & Miles, 1992), which suggests that sounds varying over time cause more disruptions. A sound that is constant in intensity or timbre should therefore cause fewer disturbances than sounds that constantly change their characteristics. A more uniform sound source can be created by filtering out high frequency sound, so called low-pass filtering (Jones, Alford, Macken, Banbury, & Tremblay, 2000) or by introducing new sources of sound, which either can be competing voices (babble-effect) or speech neutral masking noises, e.g. from ventilation (Loewen & Suedfeld, 1992). Increasing the number of sounds beyond a critical level causes the overall degree of

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variability in sound to drop, hence the overall result is a more even sound level where peaks and troughs from individual sound sources are cancelled out (Perham, Banbury, & Jones, 2007). The degree of variability might also be expected to drop when reverberation time increases. For example, Beaman and Holt (2007) found that a reverberation time, i.e. the time it takes for sound to attenuate, of 5 s led to the same low amount of error in conducting an immediate recall test as in the quiet control condition. However, in an office environment the reverberation time seldom approaches 5 s but varies in lower ranges (between 0.4 and 1 s). Perham et al. (2007) investigated if more realistic differences in reverberation time can affect performance on a cognitive test measuring serial recall. They compared one quiet condition with two different noisy conditions. The two noisy conditions were comprised of noise from various sources in an office recorded in a room with a reverberation time of either 0.7 or 0.9 s. The respondents conducted the test while listening to the noises through headphones. Although they found an effect on performance between the quiet condition, where no noise was played, and the two noisy conditions, performance on the test did not differ between the two noisy conditions. Further analyses revealed that speech intelligibility did not differ between the two noisy conditions, and the authors concluded that “at least for typical office reverberation times, lower reverberation times do not increase intelligibility” (Perham et al., 2007, p. 843). It has also been found that different noise types, for example speech, music, and office noise in general, in comparison with quiet conditions, negatively impact different cognitive outcomes, such as memory performance, reading comprehension, and proofreading (see Hongisto, 2005 for an overview).

Noise has also been extensively studied in field studies. Ringing telephones, air conditioning, and office machinery have all been suggested to cause disturbances in office environments. Human speech (Boyce, 1974; Pierrette, Parizet, Chevret, & Chatillon, 2014; Sundstrom et al., 1994) and its intelligibility is another common distracting factor. It is measured by the Speech Transmission Index (STI), which ranges from 0, meaning that the speech is not understandable, to 1, meaning that the speech is fully comprehendible. When STI exceeds 0.2 it begins to cause a decrease in performance with the highest decrement occurring around 0.6 (Hongisto, 2005). Furthermore, field studies also show that distractions and noise are present also in cell offices (Seddigh et al., 2015), even if open-plan office environments usually are associated with more noise and distractions (Kaarlela-Tuomaala et al., 2009; Seddigh, Berntson, Bodin Danielson, & Westerlund, 2014). Consequently, it would be more relevant to investigate the impact of different sound intensities or certain aspects of noise rather than comparing its presence with absence.

In addition, another study by Pierrette et al. (2014) could not find any association between the A-weighted sound pressure level dBA (LeqA) and the perception of noise in the office as high or annoying. The authors emphasised the relevance of measuring behavioural outcomes to appraise the appropriateness of the noise in open-plan office environment instead of relying overly much on objective acoustical measures. This conclusion corresponds well with the definition of noise not as the particular type or magnitude of the sound, but rather as the perception of the sound by the listener, i.e. to what extent the sound is experienced as noise (Roelofsen, 2008).

Additionally, knowledge workers – that is workers who create, develop, manipulate, disseminate or use knowledge to provide an outcome – depend to high degree upon processing information (Bosch-Sijtsema, Ruohomäki, & Vartiainen, 2010; Janz, Colquitt, & NOE, 1997). According to the Load theory of selective attention and cognitive control (Lavie, Hirst, de Fockert, & Viding, 2004) unwanted stimuli such as noise need to be first processed and then actively inhibited in order to not distract the person who is exposed to noise. Therefore, for knowledge workers noise competes for the same cognitive capacities that process task related information (see also Diamond, 2013; Seddigh et al., 2014). Hence, lower in comparison to higher noise levels in office environments should lead to fewer problems for knowledge workers.

Furthermore, another relevant theory concerning supportive design (Ulrich, 1991) suggest that while certain physical characteristics may not affect employees negatively per se, they may intensify the negative impact of some other factor in the environment (Evans, 2001). Leather et al. (2003) found such effect and reported that high noise together with high job strain, in contrast to low job strain, was associated with lower job satisfaction, lower organisational commitment and increased rate of symptoms of infectious diseases. Low noise regardless of the level of job strain did not have a large effect on these measures. A comparable suggestion to the interaction of noise level and job strain can be made for the joint effect of open-plan office environments and noise levels. That is, even if the open-plan office environments per se do not affect employee health and performance, bad acoustical conditions in these environments might.

It is important to investigate the total acoustical condition in the office rather than focussing on any single aspect that may affect the acoustical condition. Namely even if wall panels can affect the acoustical condition in an office environment, in research settings it is important to focus on the actual acoustical condition in the office instead of the presence or absence of panels per se. In fact in a recent study Leder et al. (2015) found that larger workstations in open-plan offices were associated with greater satisfaction with privacy, however the degree of enclosure of the workstation by partial-height partitions was not associated with the same outcome measure. Furthermore, in order to more thoroughly understand the impact of noise on office workers health and performance, different types of measures should be used. Except behavioural outcomes, we believe that a more comprehensive mapping of the objective sound environment, rather than too much reliance on a single sound measure, could give a more extensive understanding of how objectively measured sound is associated with the perception of noise. This idea is in fact raised in the International Standard of room acoustic parameters (ISO-3382-3, 2012), which suggests that rather than relying too much on single measures, such as reverberation time, a combination of measures including STI and background noise levels should be focused on in order to receive a more complete evaluation.

Hence, the purpose of the present study is to test the effect of different acoustical environments on employee ratings on indicators of disturbances, health, and performance. This is done by a crossover design that compares two different types of sound absorbents installed in contrasting sequences on two similar floors within the same office building. In order to obtain a comprehensive understanding of the room acoustics, we collected objective acoustical data in accordance with the international standard regarding room acoustics parameters (ISO-3382-3, 2012). We also collected behavioural measures, in order to understand how the acoustical environment impacts on the employees.

1.1. Aims and hypotheses

In this study the aim was to investigate if enhanced or worsened room acoustic characteristics in open-plan office environments are reflected in changes in the employees' own perception of disturbances, health and/or performance. The manipulation consisted of different acoustic elements in the office building, where one condition enhanced the acoustic environment (better condition) and one worsened the acoustic environment (worse condition) as compared with a baseline condition. Disturbances are examined from three different perspectives. Firstly, a broad measure of disturbances was used in order to understand the impact of our manipulation of the environment on disturbances in general. The second and third measure of disturbances focused on disturbances from sounds from nearby and distant sources, respectively. Apart from the self-rated measures, we also used objective acoustical measures.

The respondents' perception of the environment is followed over three time-points (T1, T2, and T3). Our overall hypothesis was that the acoustical conditions would have an impact on the respondents' experiences regarding the outcome variables, that is within each floor:

Hypothesis 1. *the better condition is associated with lower disturbances in general*,

Hypothesis 2. *the better condition is associated with lower nearby disturbances*,

Hypothesis 3. *the better condition is associated with lower distant disturbances*,

Hypothesis 4. *the better condition is associated with lower cognitive stress*,

Hypothesis 5. *the better condition is associated with higher professional efficiency*.

2. Method

2.1. Participating organization and employees

Two months before the study started the organisation had moved from an old office building with mostly private office rooms to a new renovated building with 6 floors, which was where this study was conducted. Two out of the six floors were used for the study (floors 4 and 5) as they had identical layouts, were similarly furnished, and the employees on these floors had similar work assignments. Each floor was highly open, with limited or no partitions, carpeted and with ceilings furbished with highly sound absorbent tiles. Each employee had his/her own designated desk.

The sample consisted of 151 employees in a municipality office outside of Stockholm, Sweden. The improvements in acoustics were partly made through installation of wall absorbents. However, the wall absorbers had not been aired before they were set up and during the initial days three employees felt irritation in the form of smell and headaches. These three employees were excluded from the analyses. A number of randomly selected employees were asked if they had noticed any smell or symptoms, but no one else had. During data collection a fourth employee received a screen that would protect against glare. Because her acoustic environment may have changed due to the screen she was also excluded from the analyses. Further, two employees on the managerial level had been informed about the design of the study and were also excluded. After exclusion of these individuals the sample size consisted of 145 persons. 77% (n = 117) of the total sample completed the baseline survey in its entirety (T0), 70% (n = 106) the first survey (T1), 62% (n = 94) the second (T2), and 64% (n = 97) the third (T3). In total around 40 individuals had a full set of data for T1, T2 and T3.

2.2. Study design and procedure

This study employed a crossover design in an office environment to investigate if enhanced and worsened acoustical environment impact employees' perception of disturbances, self-rated health and performance. Before data was collected the employees were invited to a meeting where they were informed about the purpose and procedure of the study. They were told that four electronic surveys would be sent out and that during the total time of the study, we might change the acoustics of the office several times. They were also told that at the end of the study they would be given full information about the results of the study and what changes we had made.

The baseline survey was collected just before any manipulations were made to the office environment. Each manipulation resulted in one of two conditions: In the better condition, sound absorbing wall panels were set up and the pre-existing, highly sound absorbent ceiling tiles were kept. In the so called worse condition, there were no sound absorbing wall panels and highly sound reflective ceiling tiles were installed, replacing 55% of the original highly absorbent tiles. Both types of tiles had similar colour and form and could not easily be distinguished from each other (See Zalyaletdinov, 2014 for the full acoustical report).

During the weekend after the baseline survey (T0) had been collected, changes were made on floor 4 to create the better condition, and on floor 5 to create the worse condition. Two weeks after the first manipulations had been made the first survey was sent out. The surveys were always sent out on Mondays. During the weekend after, floor 4 was changed to create the worse condition and vice versa. After two weeks of exposure to the new conditions, the second survey was sent out. The three weeks following after the second survey contained many national holidays. In order to ensure that most employees had been exposed to the sound environment for two full weeks, the third survey were sent out six weeks after the second survey had been completed (see Fig. 1).

2.3. Survey measures

All respondent data was collected by means of an electronic survey.

Disruption in general was measured by four items. The questions were “To what extent have you in the past seven days been disturbed by ventilation sounds”; “… by sounds from computers”; “… by ringing phones”; and “… by colleagues' phone calls”. All questions concerning disruptions were measured by using a five-point rating scale (1 = “to a small extent”, 5 = “to great extent”). Cronbach's α for internal reliability from the first survey was 0.71, indicating satisfactory consistency.

Nearby disturbances were measured by the question “To what extent have you in the past seven days been disturbed by speech and laughter from colleagues sitting near you (within a radius of 10 m)”.

Distant disturbances were measured by the question “To what extent have you in the past seven days been disturbed by speech and laughter from colleagues who sit further away (beyond a radius of 10 m)”.

Cognitive stress was measured by the cognitive stress scale (4 items) from the Swedish version of the Copenhagen Psychosocial Questionnaire (COPSOQ) (Kristensen, Hannerz, Høgh, & Borg, 2005). Sample question: How much of the time during the past week have you found it difficult to think clearly? All items were scored on a 5-point rating scale (1 = never, 5 = always). Cronbach's α for internal reliability from the first survey was 0.88, indicating satisfactory consistency.

The professional efficacy subscale (6 items) of the Swedish version of the Maslach Burnout Inventory – General Survey (MBI-GS) was used to assess self-rated performance (Schutte, Toppinen, Kalimo, & Schaufeli, 2000). All items were scored on a 7-point rating scale (ranging from 1 = never, 7 = daily). Cronbach's α for internal reliability from the first survey was 0.85, indicating

Fig. 1. Illustrating the process of data collection. W1 – W14 = Week 1 to week 14. C T0 to C T3 = Collection period for data at T0 to T3. Week 9–11 contained many national holidays which was handled by postponing the last manipulation and the last data collection (T3) so that everybody would be exposed to the last condition for at least two weeks before answering the survey. Each manipulation was made at the weekends following week 2, 5 and 10 as illustrated in the figure.

satisfactory consistency. See Table 1 for a correlation matrix between the dependent variables at T0.

The covariates included in the model were age (continuous: ranging from 21 to 69), gender (0 = male, 1 = female), and educational level (dichotomized: 0 = low for those without an academic degree, 1 = high for those with an academic degree; see Tables 2a and 2b).

2.4. Acoustic measurements

We included several acoustical measures in accordance with ISO 3382-3 guidelines (ISO-3382-3, 2012). These are D_2,*s*, L_p,*A*,*S*,*4* m, and *radius of comfort* (r_c). D_2,s is a rate of spatial decay of A-weighted sound pressure level of speech per distance doubling. D_2,s is therefore a measure of how fast the decibel level has been attenuated at a certain point from the sound source. L_p,A,S,4 m is a nominal A-weighted sound pressure level of normal speech at a distance of 4.0 m from the sound source. In other words L_p,A,S,4 m shows how much normal speech sound has been attenuated at a distance of 4 m from the sound source.

Radius of comfort (r_c) is the distance from the sound source where the sound pressure level of speech meets 48 dBA, which is the targeted value of $L_{p,}$A,S,4 m according to (ISO-3382-3, 2012). The radius of comfort formula was suggested at EuroNoise 2012 with background from the field study report made by Nordic Innovation (Hellström & Nilsson, 2010). The formula for calculating rc is $r_c = 4 \times 10^{0.3(L_{p,A,S,4m} - L_c)/D_{2,s}}$. These measurements were carried out for each condition in furnished rooms without staff along four measurement paths, two paths on each floor (please see Appendix for a more detailed description of the objective measurements).

In addition, dBA levels were recorded from four points by two microphones on each floor. Point 1 and 2 on floor 5 and point 3 and 4 on floor 4. These microphones registered the equivalent dBA for every 30 min interval from 06.30 until 18.00 h. Our intention was to register dBA levels for the total period, however, technical difficulties prohibited us from collecting data at point 1 during the first period and at point 2 during the third period. The length of the data collection for the dBA levels were 11 days for the first period, 4 complete days for the second period, and 15 days for the third period. Weekends were not included in the analysis. At each point for each period, an equivalent dBA was calculated for every past half an hour starting from the first registration at 7 AM to the last at 6 PM.

All objective acoustical data were gathered in order to confirm that the manipulations we had made to the physical environment had led to two distinguishable acoustical conditions on each floor.

The acoustic conditions for each path were the same for T1 and T3, hence the objective measures concerning D_2,s, L_p,A,S,4 m, and r_c measured at T1 were assumed being the same at T3.

2.5. Data analyses

39 employees had at one or several time points worked in the open-plan office environment less than 15 h the latest 7 weekdays before answering the survey. The answers of these employees at the specific time point(s) were removed. That is, if an employee had worked less than 15 h the latest 7 days before answering the survey at T1 and T3 but more than 15 h the latest 7 days before answering the survey at T2, the responses at T1 and T3 were removed while the responses at T2 were kept.

First, five 3 × 2 repeated ANCOVA analyses were carried out for each of the five outcome variables for T1, T2, and T3 in order to test if the different order of the better versus worse conditions generated a different development of the outcome measures over time.

By investigating if the quadratic function of time and floor was significant, the repeated ANCOVAs test if the repeated manipulations to the different floors affected the outcome measures in the supposed direction. That is, the exposure for each floor either went from better to worse to better (floor 4), or from worse to better to worse (floor 5) which was hypothesised to yield approximately symmetrically different U-shape curves of the outcome variables for the two floors that significantly differed in their direction. Employees on floor 4 should rate Disruption in general, Nearby disturbances, Distant disturbances, and Cognitive stress as low (in the better condition) – high (worse condition) – low (better condition) creating a ∩-shaped pattern, while employees on floor 5 should rate the same outcomes as high (worse condition) – low

Table 1
Correlation between outcome variables at T0.

	Disruption in general	Cognitive stress	Disturbances near	Distant disturbances	Professional efficiency
Disruption in general	1	0.43[b]	0.76[b]	0.64[b]	−0.17
Cognitive stress		1	0.37[b]	0.35[b]	−0.35[b]
Disturbances near			1	0.58[b]	−0.22[a]
Distant disturbances				1	−0.16
Professional efficiency					1

[a] Correlation is significant at the 0.05 level (2-tailed).
[b] Correlation is significant at the 0.01 level (2-tailed).

Table 2a
Demographic characteristics of the respondents.

	n[a]	Sex[a] (female) %	Age in years[a]	Educational level (high) %[a]	Disruption in gen. T0	Disturbances near T0	Distant disturbances T0	Cognitive stress T0	Professional efficiency T0
					Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]
Floor 4	59	58	44.8 (12.2)	61	3.1 (1.1) [41]	2.6 (1.3) [41]	2.0 (1.1) [41]	2.3 (0.8) [40]	5.4 (0.7) [40]
Floor 5	86	57	43.3 (11.9)	86	3.0 (1.1) [51]	2.3 (1.3) [53]	2.2 (1.2) [53]	2.4 (0.7) [53]	5.4 (0.7) [51]
Total	145	57	43.9 (11.9)	75	3.0 (1.1) [92]	2.4 (1.3) [94]	2.1 (1.2) [94]	2.3 (0.7) [92]	5.4 (0.7) [91]

[a] Based on the analytic sample. Age is based on 143 respondents given that for two employees age was missing. The scale for Disruption, disturbances near, distant disturbances ranged from 1 = "to a small extent" to 5 = "to great extent", the scale cognitive stress ranged from 1 = "never" to 5 = "always" and the scale Professional efficacy ranged from 1 = "never" to 7 = "daily".

Table 2b
Mean, standard deviation and n for the employees who had been working more than 15 h the latest 7 days before answering each survey.

	Disruption in gen. T1	Disturbances near T1	Distant disturbances T1	Cognitive stress T1	Professional efficiency T1	Disruption in gen. T2	Disturbances near T2	Distant disturbances T2	Cognitive stress T2	Professional efficiency T2
	Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]
Floor 4	3.2 (1.1) [40]	2.6 (1.3) [40]	2.1 (1.2) [40]	2.2 (0.7) [38]	5.3 (0,7) [37]	3.5 (1.2) [32]	3.12 (1.3) [33]	2.5 (1.3) [33]	2.4 (0.9) [33]	5.2 (0,8) [31]
Floor 5	3.6 (1.3) [45]	2.7 (1.4) [46]	2.7 (1.5) [46]	2.7 (0.7) [46]	5.3 (0.8) [46]	3.2 (1.3) [37]	2.4 (1.5) [37]	2.3 (1.4) [37]	2.4 (0.7) [37]	5.3 (0.9) [36]

	Disruption in gen. T3	Disturbances near T3	Distant disturbances T3	Cognitive stress T3	Professional efficiency T3
	Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]	Mean (sd) [n]
Floor 4	3.4 (1.2) [29]	3.1 (1.1) [31]	2.3 (1.2) [30]	2.4 (0.7) [30]	5.3 (0,8) [30]
Floor 5	3.8 (1.3) [42]	3.0 (1.3) [43]	2.7 (1.4) [43]	2.8 (0.9) [42]	5.1 (1.1) [40]

(better condition) – high (worse condition) creating a U-shaped pattern. For professional efficiency employees on floor 4 should rate as high (better condition) – low (worse condition) – high (better condition) creating a U-shaped pattern, while employees on floor 5 should rate professional efficiency as low (worse condition) – high (better condition) – low (worse condition) creating a ∩-shaped pattern.

A significant quadratic function of time and floor would mean that the better and worse conditions affected the employees according to intentions, which will allows us to conduct further analyses to test if the manipulations between the better and the worse conditions differed meaningfully within each floor.

Second, on floor 4 and 5 separate repeated ANCOVAs were carried out. For floor 4 these tested if the first better condition (T1) significantly differed from the worse condition (T2) (the first contrast analysis) and if the second better condition (T3) significantly differed from the worse condition (T2) (the second contrast analysis). For floor 5 these tested if the better condition (T2) differed significantly from the first worse condition (T1) (the third contrast analysis), and if the better condition (T2) differed significantly from the second worse condition (T3) (the fourth contrast analysis). These additional analyses were carried out only for the outcomes that were significant in the first set of analyses investigating the quadratic interaction effect of time and floor on the outcomes.

The analyses were conducted in SPSS version 21 by means of the General Linear Model. Sex, age, and educational level were included as covariates. The repeated ANCOVA analyses rely on non-missing-data for each respondent for T1–T3. Hence, for each ANCOVA analyses missing answers at T1, T2 and/or T3 for each outcome variable lead to case-wise deletion.

3. Results

The difference between the better and the worse acoustical condition for the active parts of the working days and for each floor are shown in Fig. 2, which illustrates that in general throughout the days during data collection, both floors had a lower dBA level during the better condition in comparison to the worse. Floor 5 had a larger variation than floor 4. The figure also shows a trend that the dBA levels seem to increase from morning to the late afternoon. For the other objective measures please see Table 3.

According to expectations, and as shown in Table 3, the condition with both absorbing tiles and wall absorbents, absorbed noise better than the condition with reflective tiles and no wall absorbents according to the latest ISO standard.

3.1. Disruption in general

According to Wilks' criterion there were no significant main effects of time or floor. The interaction effects between time and the covariates were not significant. The time and floor interaction was significant for the hypothesised quadratic function ($F[1, 38] = 7.29$, $p = 0.01$, partial $\eta^2 = 0.16$). The manipulations on each floor yielded symmetrically different U-shaped curves for disruption in general which suggested lower disturbances in the better conditions in comparison to the worse. Contrast analyses comparing the conditions within each floor where carried out to test the first hypothesis. On floor 4 the change from the better (T1) to the worse (T2) condition was significant while the change from the worse (T2) to the better (T3) condition was not. On floor 5 the change between the worse (T1) to the better (T2) condition was not significant but the change between the better condition (T2) to the worse (T3) was significant (all $p < 0.05$; please see Fig. 3a). To conclude, the first hypothesis was supported in that the better acoustical condition is related to less reported disturbances in general.

3.2. Nearby disturbances

With the use of Wilks' criterion there was no significant main effect of time or floor. The interaction effects between time and the covariates were not significant. The time and floor interaction was significant between time and floor for the hypothesised quadratic function ($F[1, 40] = 16.69$, $p < 0.001$, partial $\eta^2 = 0.29$). The manipulations on each floor yielded symmetrically different U-shaped curves for nearby disturbances, which suggested lower

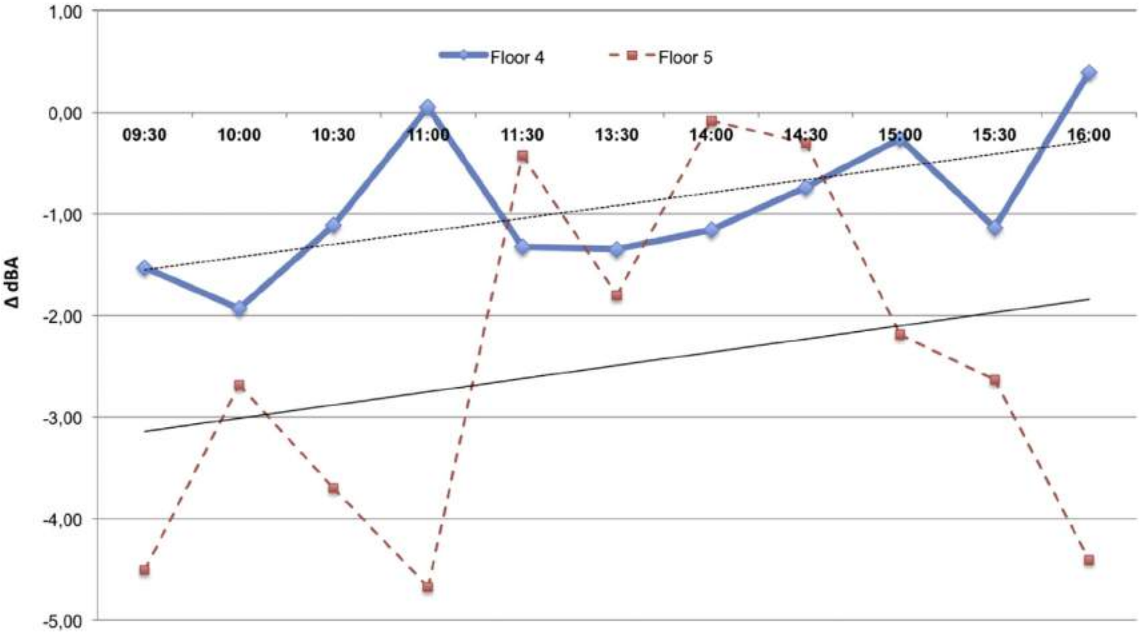


Fig. 2. The sound pressure level (dBA) difference between the better and the worse acoustical condition for the active parts* of the working days and for each floor. The differential is an aggregated mean for the specified time intervals across the total duration of the study. Each line represents in general how much lower dBA levels were in the better condition as compared with the worse at different time-points throughout the working days. *Active parts = parts of the day that the office is appraised being busy, that is the total day except early morning, lunch time and late afternoon. Below zero suggest that the quiet acoustical condition was associated with lower dBA levels. The lower straight line shows the trend for floor 5 while the upper straight line shows the for floor 4. The total mean for the active parts for floor 4 during the better condition was 46 dBA and the mean for the worse condition was 47 dBA. The total mean for the active parts for floor 5 during the better condition was 45 dBA and the mean for the worse condition was 47 dBA.

Table 3
Objective acoustic measures on floor 4 and 5 for the different conditions.

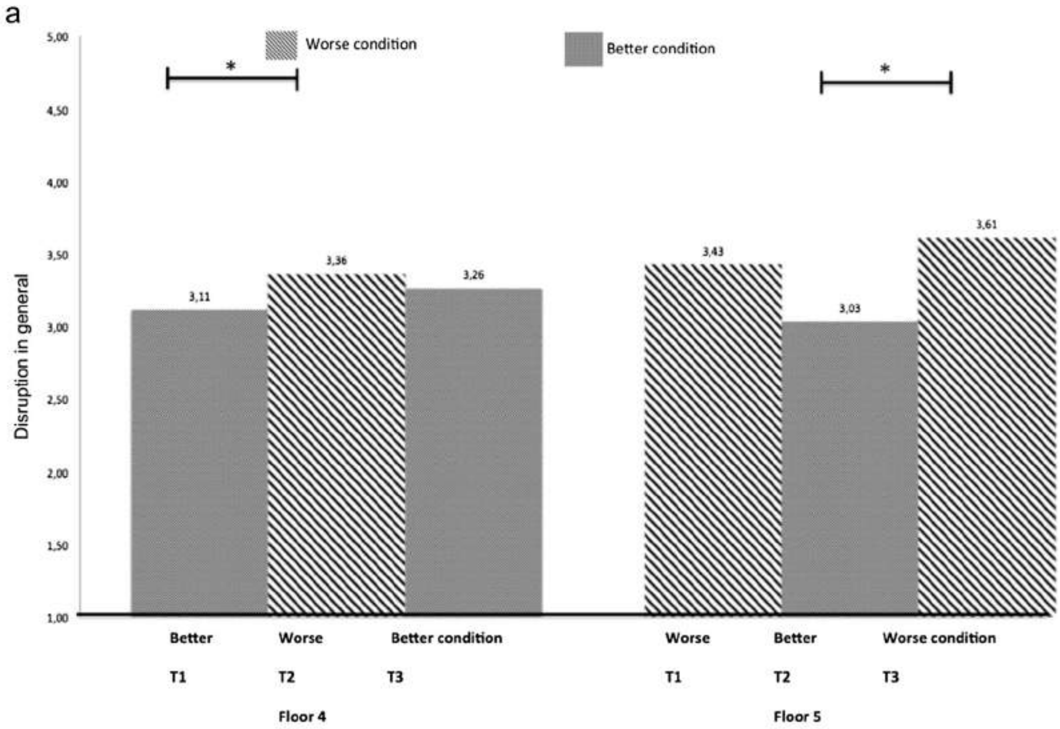
Floor	Path	Time period	Description of the condition	$D_{2,S}$ [dB]	L_p,A,S,4 m [dB]	r_C [m]
4	1	T0	Original condition (absorbing tiles)	4.9	48.2	4.5
4	1	T1 & T3	Better condition (absorbing tiles with wall absorbents)	4.9	47.8	4.2
4	1	T2	Worse condition (reflective tiles)	4.0	49.0	5.3
4	2	T0	Original condition (Absorbing tiles)	4.5	50.1	6.1
4	2	T1 & T3	Better condition (absorbing tiles with wall absorbents)	4.9	49.3	5.2
4	2	T2	Worse condition (reflective tiles)	3.6	50.2	6.8
5	1	T0	Original condition (absorbing tiles)	5.0	47.0	3.8
5	1	T1 & T3	Worse condition (reflective tiles)	4.5	49.5	5.5
5	1	T2	Better condition (absorbing tiles with wall absorbents)	5.3	46.7	3.7
5	2	T0	Original condition (absorbing tiles)	6.6	48.1	4.3
5	2	T1 & T3	Worse condition (reflective tiles)	6.8	50.2	5.3
5	2	T2	Better condition (absorbing tiles with wall absorbents)	6.8	47.1	3.9

D_2,s is a rate of spatial decay of A-weighted sound pressure level of speech per distance doubling and L_p,A,S,4 m is a nominal A-weighted sound pressure level of normal speech at a distance of 4.0 m from the sound source. Rc is calculated by the following formula: $r_c = 4 \times 10^{0.3(L_{p,A,S,4m} - L_c)/D_{2,s}}$.On each floor the objective measure were made on two different paths, illustrated as 1 or 2 beneath the column Path. The acoustic settings were exactly the same for T1 and T3 for each path and gathered only at one time point.

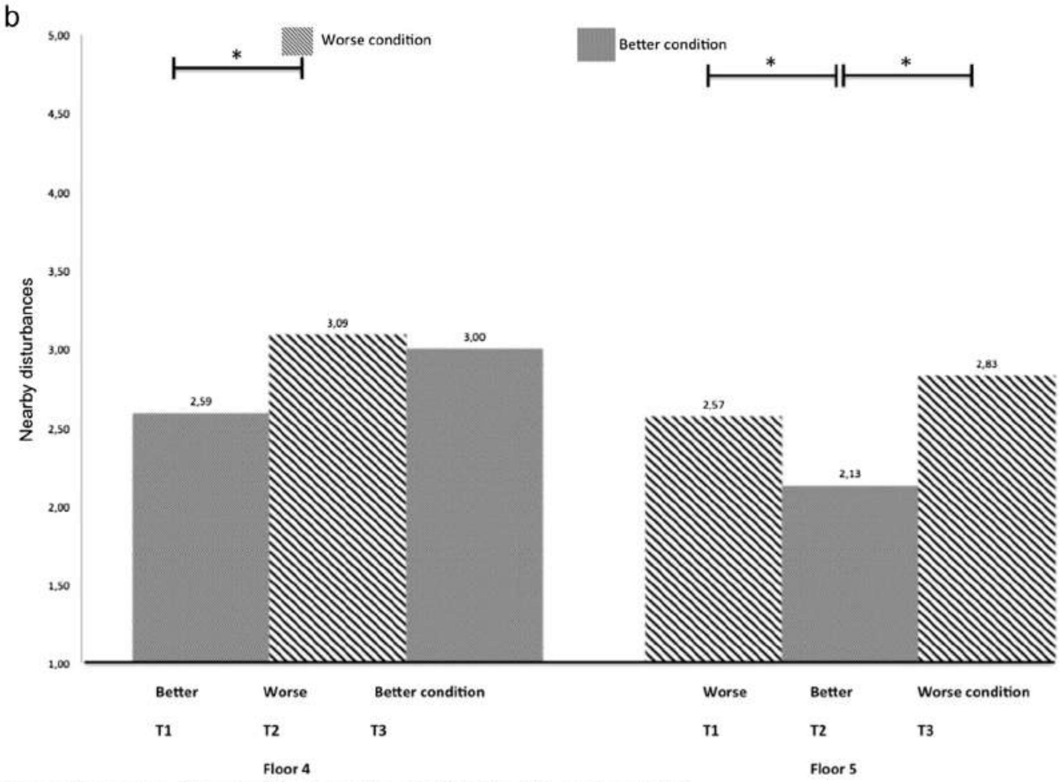
disturbances in the better conditions in comparison to the worse. Contrast analyses comparing the conditions within each floor showed that on floor 4 the change from the better (T1) to the worse (T2) condition was significant while the change from the worse (T2) to the better (T3) condition was not. On floor 5 the change between the worse (T1) to the better (T2) condition was significant which also was the change between the better condition (T2) to the worse (T3) (all $p < 0.05$; please see Fig. 3b). To conclude the second hypothesis was supported in that the better acoustical condition is related to lower reported nearby disturbances.

3.3. Distant disturbances

With the use of Wilks' criterion there was no significant main effect of time or floor. The interaction effects between time and the covariates were not significant. The time and floor interaction was significant between time and floor for the hypothesised quadratic function ($F[1, 40] = 5.42$, $p = 0.025$, partial $\eta^2 = 0.12$). The manipulations on each floor yielded symmetrically different U-shaped curves for distant disruption suggested lower disturbances in the better conditions in comparison to the worse. Contrast analyses comparing the conditions within each floor where carried out to test the first hypothesis. On floor 4 neither the change from the better (T1) to the worse (T2) condition nor the change from the worse (T2) to the better (T3) condition was significant. On floor 5 the change between the worse (T1) to the better (T2) condition was not significant but the change between the better condition (T2) to the worse (T3) was significant (all $p < 0.05$; please see Fig. 3c). To conclude, the third hypothesis was supported in that the better acoustical condition is related to less reported disturbances from distant sources.

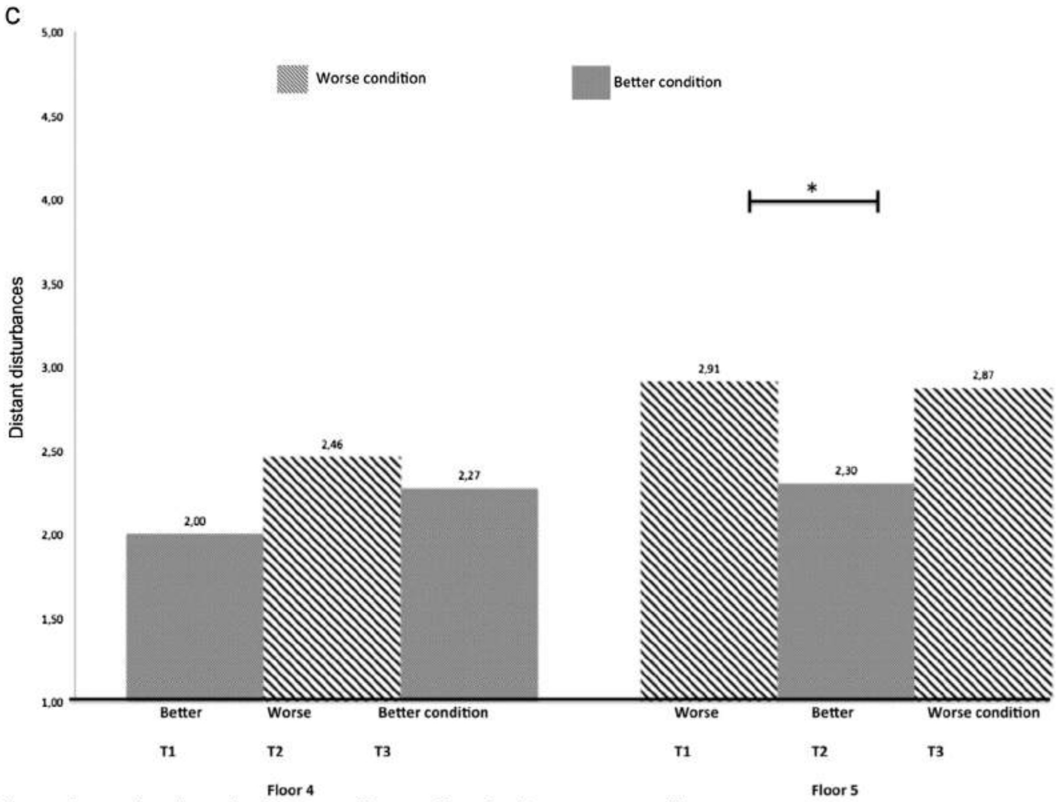


The scale ranging from 1 = “to a small extent” to 5 = “to great extent”.
* = p< 0.05.

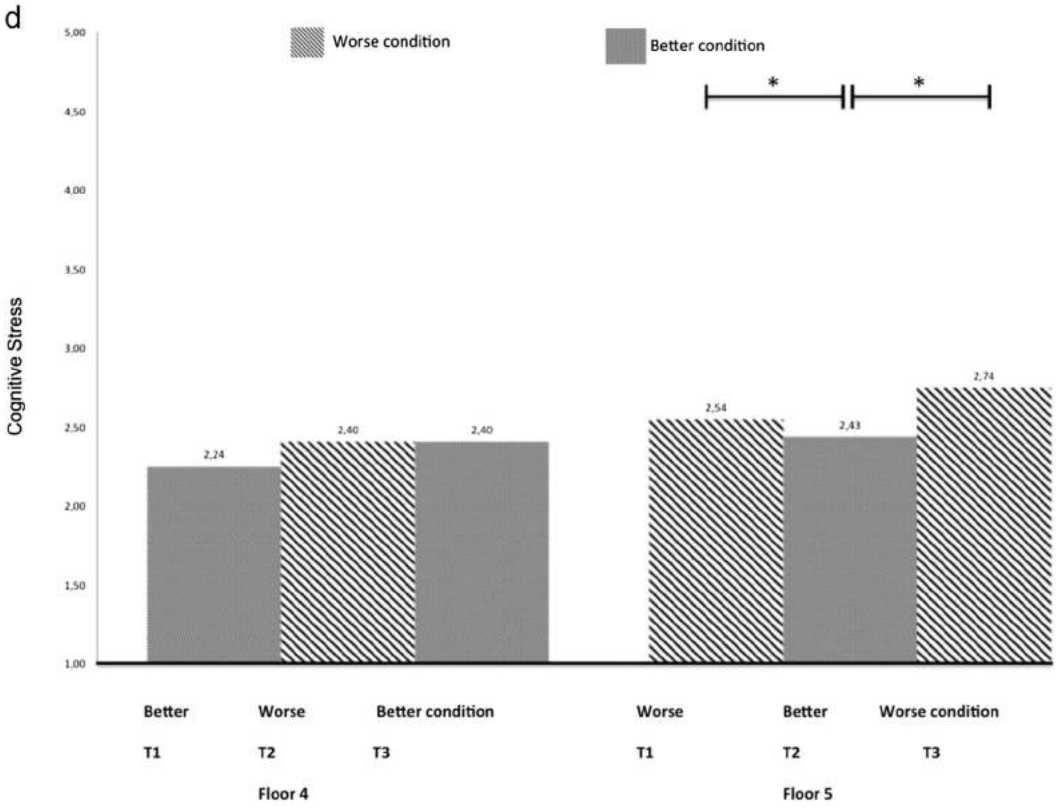


The scale ranging from 1 = “to a small extent” to 5 = “to great extent”.
* = p< 0.05.

Fig. 3. a. Mean for Disruption general at T1–T3 for floor 4 and floor 5. b. Mean for Nearby disturbances at T1–T3 for floor 4 and floor 5. c. Mean for Distant disturbances at T1–T3 for floor 4 and floor 5. d. Mean for Cognitive stress at T1–T3 for floor 4 and floor 5. e. Mean for Professional efficiency at T1–T3 for floor 4 and floor 5.

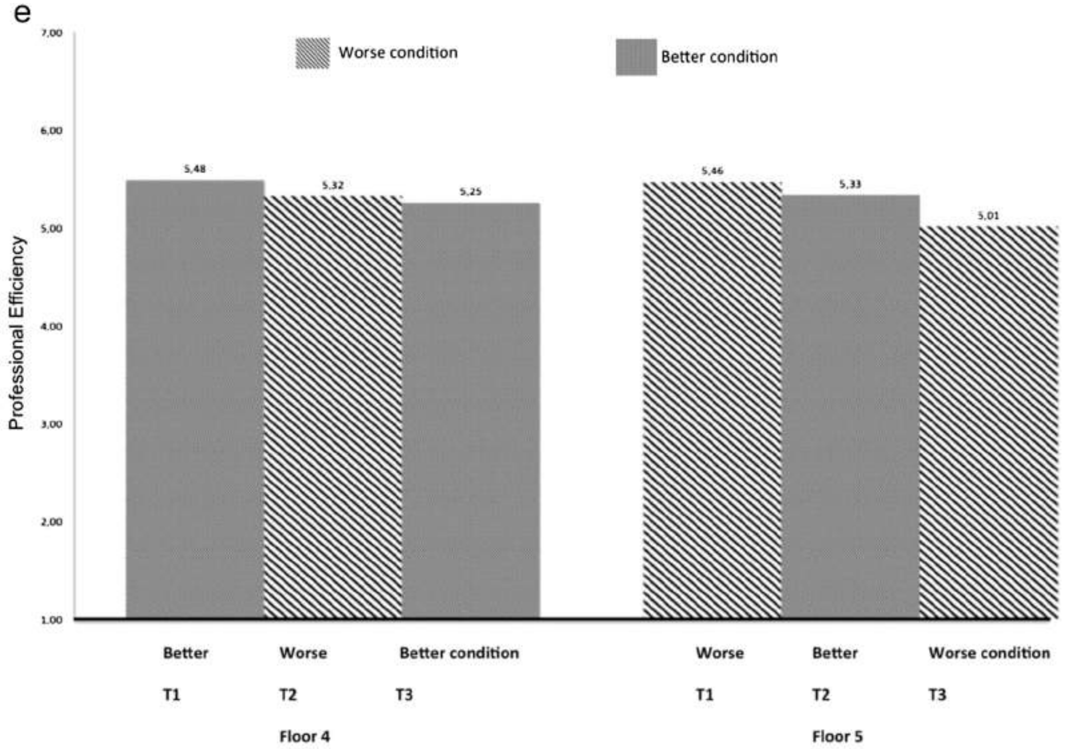


The scale ranging from 1 = "to a small extent" to 5 = "to great extent".
* = $p < 0.05$. # = $p = 0.05$.



The scale ranging from 1 = "never" to 5 = "always".
* = $p < 0.05$.

Fig. 3. (*continued*).



The scale ranging from 1 = “never” to 7 = ”daily”.

Fig. 3. (*continued*).

3.4. Cognitive stress

With the use of Wilks' criterion there was no significant main effect of floor. However, the main effect of time was significant (F[2, 36] = 3.48, p = 0.042, partial $\eta^2 = 0.16$). The interaction effect between time and covariates were not significant. The time and floor interaction was significant between time and floor for the hypothesised quadratic function (F[1, 37] = 7.59 p = 0.009, partial $\eta^2 = 0.17$). The manipulations on each floor yielded symmetrically different U-shaped curves for cognitive stress, which suggested lower stress in the better conditions in comparison to the worse. Contrast analyses comparing the conditions within each floor where carried out to test the fourth hypothesis. On floor 4 neither the change from the better (T1) to the worse (T2) condition nor the change from the worse (T2) to the better (T3) condition were significant. On the other hand on floor 5 both the change between the worse (T1) to the better (T2) condition and the change between the better condition (T2) to the worse were significant (all $p < 0.05$; please see Fig. 3d). To conclude, the fourth hypothesis was supported in that the better acoustical condition is related to less cognitive stress.

3.5. Professional efficiency

With the use of Wilks' criterion there was no significant main effects of floor or time. The interaction effects between time and the covariates were not significant. Further, the hypothesized quadratic function between time and floor was not significant (see Fig. 3e), meaning that the employees on each floor did not report significantly higher or lower efficiency depending on the different conditions. Given that the overall quadratic function of time and floor was not significant, no further analyses within each floor were carried out. Therefore the fifth hypothesis could not be supported (see Fig. 3e).

4. Discussion

This study investigated if better and worse acoustic environments, created by less or more absorbing tiles and wall absorbents, affect employees' perception of disturbances, cognitive stress, and professional efficacy.

In line with our expectations, the acoustical measures showed a lower overall noise level during the working day and also lower D_2,s, L_p,A,S,4 m, and r_c in conditions where tiles and wall panels that absorbed more sound energy had been installed. In addition, also supporting our expectations, the acoustical measures showed a higher overall noise level during the working day and higher D_2,s, L_p,A,S,4 m, and r_c in conditions where the more reflective tiles where installed and wall panels removed.

Our results are in line with previous studies (Kaarlela-Tuomaala et al., 2009) and suggest that employees' perception of disturbances and health are affected negatively when exposed to increased noise levels. However, in contrast to previous research findings (Perham et al., 2007; Pierrette et al., 2014), the results from the present study showed that improved room acoustics was associated not only to lower objective noise levels, but also to lower perceived disturbances and lower cognitive stress. Consequently, the results imply that employees perceived better possibilities to make decisions, concentrate, and reported having lower amount of memory loss. These findings may be explained by that decreased general noise level in the office environment decrease the interference of noise on higher cognitive functions, which are important for knowledge workers ability to carry out their tasks (Diamond, 2013; Lavie et al., 2004; Seddigh et al., 2014, 2015). These findings can also be related to the findings of Leather et al. (2003) who reported that high noise levels in contrast to low noise levels interact with job strain and impact employees' job satisfaction, organisational commitment and symptoms of infectious diseases. Hence, the acoustical condition of the open-plan office seems to have a direct relationship to indicators of both health and performance of employees.

Interestingly, these effects were evident despite the short exposure time to the new condition, suggesting that the effect of a change in room acoustics is quite immediate. However, the short exposure time might also explain why not all contrast analyses where significant, even if the effects went in the expected direction (i.e. better acoustics leading to less problems, for our measures of disturbances and health).

As evident in Fig. 1, the manipulations between the two conditions had a larger impact on floor 5 in forms of differences in dBA-levels. Although the employees on both floors had similar tasks, one possible explanation to these differences was revealed during the feedback session to the employees. Employees on floor 5 had more conversations and meetings around their desks and in the open space compared to employees on floor 4 who either did not have as many meetings or conducted the meetings in separate meeting rooms. Therefore, the acoustical differences between the two acoustical conditions likely had greater consequence for floor 5 than for floor 4, as Fig. 1 illustrates. In fact it is possible to discern a similar pattern in employees' rating by looking at Fig. 3a–e. Also in these figures it is apparent that the differences between the better and worse condition is larger on floor 5 as compared to floor 4, meaning that manipulations on floor 5 had a larger effect on the employees.

Nevertheless, also for the significant findings the survey responses have a low variation around the middle of the scale. Therefore it seems that even if noise has a significant impact it does not seem terribly disturbing to most respondents. Given the small variation in the objective measures between the conditions, our results might also indicate that quite large changes to the physical environment are needed to substantially improve the acoustical conditions in the office.

In this study we conducted acoustical measurement according to the new ISO-standards for open-plan offices (ISO-3382-3, 2012). With these measurements and radius of comfort (r_c) we could find differences which corresponded to the manipulations done to the acoustical environment. Although the acoustical measures showed quite small differences between our two conditions within each floor, a comparison of effect sizes for the sought quadratic function between time and floor reveal small effects approaching medium sized effects (η^2 between 0.15 and 0.29) (Cohen, 1988). This would suggest that even a minor improvement made to room acoustics could impact employees perceived health and disturbances.

4.1. Strengths and limitations

One of the main strengths of this present study is that it was carried out in the field addressing regular office employees. Given that the social and other organisational structure within the organisation had not changed, we believe that our finding is highly relevant for the effect that noise has on employees' perception of cognitive stress and disturbances. Another strength of this study is its crossover design. By having two groups that constantly were exposed to the opposite condition than the other and by changing back and forth between the conditions, we created a highly controlled field experiment increasing the reliability of our findings. In addition, we also gathered objective data. The objective measurements ensured that the manipulations we carried out had an impact on the acoustical environment and further strengthened our findings by corresponding to the survey responds. By so doing we were able to show that improvements in acoustics have a direct impact on measures of both health and disturbances.

The ceiling tiles of both conditions looked the same, but the wall absorbent installed during the better condition could have indicated to the respondents sitting near the wall absorbents that an improvement had been made. In turn this signal could have systematically affected the employees to respond more positively when the absorbents were present. Nevertheless, there are some aspects that speak against that our results mainly would be due to such a placebo effect. Before any manipulations were made employees on both floors were asked to answer the survey (T0). At T1 floor 5 had the worse condition – that is the condition without any wall absorbent and with reflective ceiling tiles. As we compare the result of T0 with T1 we see that these employees generally report more problems during T1 (compare Table 2a with Fig. 3a–e or with Table 2b). If our result would be due to placebo we should not have seen such pattern given that no visual manipulations had been made on floor 5 between T0 and T1. On the other hand on floor 4 and during T1 in comparison to T0, the employees rated only small improvements in disturbances and cognitive stress. This corresponds well with the minor improvements measured by the acoustical measurements conducted between T0 and T1. Therefore, all in all it seems that the employees' answers correspond well with the acoustical measurements conducted rather than the presence or absence of the wall absorbents.

Another concern that could be raised as a limitation is the short exposure period for each condition before we collected the survey data. If people after some passage of time learn to adapt to an increased noise level then our findings might not be as relevant as they might suggest. However, a study by Banbury and Berry (2005) could not find any lasting habituation to office noise, which speaks against any major adaptation to increased noise levels taking place among employees.

5. Conclusions and implications for practice

By means of a crossover design, we investigated the effect of two different room acoustics on employees' perception of disturbances, cognitive stress, and professional efficacy. Although the acoustical measurements showed that the manipulations between our two conditions in general were quite small, the better acoustical condition nevertheless had a more positive effect on employees' perception of disturbances and cognitive stress. It was also shown that manipulations in the acoustical environment measured by measurements suggested in ISO 3382-3(ISO-3382-3, 2012) correspond well with employees' self-reported measures of health and disturbances. The study shows the importance of focussing on the acoustical conditions in open-plan offices in order to improve employees' well-being and through means of that also organisational efficiency.

Authors' contribution

AS designed and made the preparation for the study. AS anchored the project in the participating organisation and also collected the data. AS conducted the analysis and wrote the first and successive draft including introduction, method, result, and discussion sections.

HW, FJ, EB, and CBD have contributed with substantial suggestions and comments to the manuscript. AS have changed the manuscript according to relevant suggestions and comments, and prepared the final manuscript. AS submitted the manuscript and is the corresponding author in the review process.

HW, FJ, and EB have been supervising AS in every part of the study, contributed to the writing of the paper, and have also been involved in the design process. HW is overall project leader.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvp.2015.08.004.

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