**Auditory distraction during reading: A Bayesian meta-analysis of a continuing controversy**

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Abstract

It has long been argued

In the current study, we report a meta-analytical investigation of k number of studies on auditory distraction effects during reading spanning over 80 years.

*Keywords*: auditory distraction, reading, background noise, speech, music

Reading is a critical skill that is indispensable in modern society. Although reading performance is best in silence when no distracting stimuli are present, such ideal conditions are rarely typical for daily life. Rather, much of everyday reading occurs in the presence of external auditory stimulation, such as noise from nearby traffic, music playing in the background, or a colleague talking on the phone. The interest in how auditory stimuli affect human performance is almost as old as modern psychology itself (e.g. Cassel & Dallenbach, 1918; Morgan, 1917). From to the widespread use of personal radios among students in the 1940s (Henderson, Crews, & Barlow, 1945; Miller, 1947) to the rise in popularity of the TV (Armstrong, Boiarsky, & Mares, 1991; Cool, Yarbrough, Patton, Runde, & Keith, 1994) and mobile devices (Kallinen, 2002), researchers and educators alike have been interested in whether background sounds can distract students from reading and other study-related tasks.

Over the past eight decades, many studies have examined how experimental exposure to speech, noise, and music affects the reading process. Although some important patterns of results have emerged, the research literature has been undermined by a fair amount of inconsistent findings and the general lack of broader theoretical frameworks that can explain how auditory distraction during reading occurs. Although a number of theoretical accounts have been developed in simpler tasks such as serial recall, it is currently not known how well they can account for all the findings from reading comprehension tasks that have been accumulated over the past several decades. Additionally, due to the mixed findings in some areas, it is currently not well understood what the magnitude of auditory distraction effects is.

In the present paper, we address these issues in two ways. First, we present the first attempt to make a statistical synthesis of previous findings in a reading task in order to find out whether, and to what extent, auditory stimuli can interfere with reading performance. To do this, we adopted a Bayesian meta-analysis approach that makes it possible to quantify the degree of belief, given the data, that background sounds can disrupt reading. Second, we used Bayesian meta-regression models to test the predictions derived from existing theories on auditory distraction and to estimate how likely it is that they can explain the available data. The present paper starts with a brief overview of the literature that highlights existing inconsistencies. Then, we consider theories that can explain auditory distraction effects during reading. Finally, the predictions from these theories are outlined and tested.

**The effect of background noise, speech, and music on reading: An overview**

**Background noise.** Although a number of epidemiological studies have suggested that chronic exposure to noise is associated with lower reading ability in children (e.g., Haines, Stansfeld, Job, Berglund, & Head, 2001; Hygge, Evans, & Bullinger, 2002; Papanikolaou, Skenteris, & Piperakis, 2015; Stansfeld et al., 2005), only few studies have examined the effect of experimental exposure to noise. In one early study, Johansson (1983) found that 10-year-old children had the same reading comprehension and reading speed under quiet conditions, and conditions of continuous, or intermittent acoustic noise. More recently, Dockrell and Shield (2006) investigated the effect of typical classroom noise on reading comprehension in 8-year-old children. Participants completed the Suffolk Reading Scale in one of three conditions: silence, noise consisting of childrens’ babble, and the same babble combined with intermittent environmental noise. The results showed that children performed better in quiet than in the babble noise condition. Surprisingly however, reading performance was best when babble was combined with environmental noise. Using similar sound stimuli, Ljung, Sorqvist, and Hygge, (2009) found that road traffic noise impaired the reading speed of 12-13-year-old children, but not their reading comprehension. However, a condition of children’s babble intermixed with irrelevant speech affected neither measure.

Studies of exposure to noise in adults have resulted in similarly mixed findings, sometimes even when done with the same materials (cf. Martin, Wogalter, & Forlano, 1988, Experiments 4 and 5). While most studies have failed to find an effect of noise on reading comprehension (Gawron, 1984; Jahncke, Hygge, Halin, Green, & Dimberg, 2011; Johansson, Holmqvist, Mossberg, & Lindgren, 2012; Veitch, 1990), others have found such an effect after examining the mediating role of personality characteristics (Furnham, Gunter, & Peterson, 1994; Ylias & Heaven, 2003). In summary, studies investigating the effect of background noise on reading comprehension have yielded inconsistent results, although some of them have suggested that exposure to noise may be detrimental.

**Background speech.** Similar to noise, background speech is also often a nuisance to readers. However, speech has different acoustic properties than noise and it also carries semantic meaning if readers are able to understand it (which is very often the case in daily life). Perhaps owing to its semantic content, background speech is often rated as more distracting and more annoying than acoustic noise (Haka et al., 2009; Haapakangas et al., 2011; Landström, Söderberg, Kjellberg, & Nordström, 2002). Consistent with this subjective perception, meaningful background speech has been found to disrupt reading comprehension in a number of experiments (Armstrong et al., 1991; Baker & Madell, 1965; Martin et al., 1988; Sörqvist, Halin, & Hygge, 2010; however, see Venetjoki, Kaarlela-Tuomaala, Keskinen, & Hongisto, 2006). Additionally, there is some evidence to suggest that this disruption effect may be larger for participants who have poorer immediate suppression mechanism to ignore the background speech (Sörqvist, Halin, & Hygge, 2010; Sörqvist, Ljungberg, & Ljung, 2010).

Due to its implications for performance at the workplace, the effect of background speech on proofreading has also been investigated. Proofreading is a more cognitively demanding task than reading because it also requires allocating attention to look for mistakes, in addition to reading the text. There are generally two types of mistakes that have been considered in proofreading studies: contextual mistakes that require understanding the meaning of the text in order to detect, and non-contextual (i.e. spelling) mistakes that require only processing of the current word to detect. Due to the semantic content of speech, it can be hypothesized that background speech would disrupt the detection of contextual errors more than the detection of non-contextual errors.

Some support for this prediction was found by an early study by Weinstein (1977) who reported that background speech consisting of radio news significantly impaired the detection of contextual, but not the detection of non-contextual errors. However, Jones, Miles, and Page (1990) found exactly the opposite effect in another study. The authors manipulated both by the intelligibility of background speech (normal vs reversed) and the intensity of the sound (50 vs 70 dBA). They found that the intensity of the sound did not affect proofreading performance, but that normal (i.e. intelligible) speech reduced the number of non-contextual errors that were detected. Critically, however, the intelligibility of speech did not affect the detection of contextual errors (Jones et al., 1990). More recently, Venetjoki et al. (2006) found that background speech compared to continuous noise reduced the overall accuracy on the proofreading task. However, even though the task included both contextual and non-contextual errors, there was no significant effect of background speech on either error type in isolation. In a similar study, Landström et al. (2002) found that background speech, compared to broadband noise, did not affect proofreading performance for either contextual or non-contextual mistakes. The background stimuli were presented at comparable sound levels to Venetjoki et al. (2006), although the speech consisted of random statements. Finally, Smith-Jackson and Klein (2009) also found no effect of background speech (intermittent or continuous) on overall proofreading accuracy.

Interestingly, a few studies have also suggested that the detrimental effect of background speech on reading and proofreading can be diminished by making the task harder and thus increasing participants’ engagement with it (Halin, 2016; Halin, Marsh, Haga, Holmgren, & Sörqvist, 2014a; Halin, Marsh, Hellman, Hellström, & Sörqvist, 2014b). In a few experiments, Halin et al. showed that performance on a reading/ proofreading task was disrupted by background speech only when the text was formatted in a familiar, but not in an unfamiliar (i.e. more difficult to read) font, and when the text was printed normally, but not when it was visually degraded (i.e. harder to read). Therefore, these results suggest that increasing task engagement may decrease the detrimental effect of background speech on reading comprehension and proofreading accuracy (see Sörqvist & Marsh, 2015 for a discussion).

The majority of studies that were considered so far have investigated only the end product of reading (i.e., comprehension accuracy or the overall time taken to read the text). However, these studies do not tell us how the reading process is influenced on a moment-to-moment basis. More recently, a number of eye-tracking studies have addressed this question by showing that the effect of background speech on reading can also be found at the level of fixation durations and fixations probabilities (Cauchard, Cane, & Weger, 2012; Hyönä & Ekholm, 2016; Vasilev, Liversedge, Rowan, Kirkby & Angele, n.d.) One of the key finding from these studies is that background speech leads to an increased number of re-reading fixations. While these studies have been successful in explaining where in the reading process disruption by background speech occurs, one puzzling aspect is that, unlike behavioural studies, none of the eye-tracking experiments replicated the effect of disruption in comprehension accuracy. It is currently not known why this inconsistency exists, but it does raise the question of how reliable the effect of background speech on reading comprehension is.

In summary, background speech has been found to disrupt reading comprehension and proofreading accuracy in a number of experiments. In addition, the available evidence suggests that this disruption is due to processing the semantic meaning of the speech sound. These effects appear to be more consistent than the effect of background noise on reading, which has not been consistently replicated. Nevertheless, the effect of background speech on reading comprehension has also had its fair share of null effects, particularly in recent years, which casts doubt on its robustness.

**Background music.** Unlike noise and speech, playing music in the background is often a personal choice or a habit. Interest in the potential effect of background music on reading started in the first half of the 20th century with the popularity of personal radios and their use by students. However, these early studies did not paint a clear picture of the relationship between background music and reading. While some of them found that music can disrupt reading comprehension in children and university students (Henderson et al., 1945; Fendrick, 1937; Fogelson, 1973), others found that background music either does not affect reading (Freeburne & Fleischer, 1952; Miller, 1947; Mitchell, 1949) or that it actually improves it (Hall, 1952). Indeed, this controversy has persisted until the present day, and even the only two eye-tracking studies to address this question (Cauchard et al., 2012; Johansson et al., 2012) have failed to find any effect of background music on fixation durations and fixation probabilities.

In order to examine what conditions may give rise to distraction,somestudies have investigated whether the effect of background music on reading comprehension is modulated by personality traits (Avila, Furnham, & McClelland, 2011; Furnham & Allass, 1999; Furnham & Bradley, 1997; Furnham, Trew, & Sneade, 1999; Furnham & Stephenson, 2007; Furnham & Strbac, 2002). Based on Eysenck’s (1967) theory of personality, these studies have predicted that individuals high in extraversion will be distracted less by background music than individuals high in introversion due to extroverts’ higher cortical arousal threshold. However, the results from these studies have been mixed. While some studies found such an interaction between personality trait and background music (Daoussis & McKelvie, 1986; Furnham & Bradley, 1997; Furnham & Strbac, 2002), others did not (Avila et al., 2011; Furnham & Allass, 1999; Furnham et al., 1999; Furnham & Stephenson, 2007). A number of factors may have led to these inconsistencies, such as the way in which participants were classified as introverts and extroverts, and the small sample size in some of the studies.

Another factor that has been considered is the genre of the music (Kallinen, 2002; Miller & Schyb, 1989; Mullikin & Henk, 1985; Tucker & Bushman, 1991). However, as the popularity of music genres changes with time, it is arguably better to investigate what aspects of the music may cause distraction. One factor that may play a role is participants’ preference for the music. For example, Etaugh and colleagues (Etaugh & Michals, 1975; Etaugh & Ptasnik, 1982) reported that preferred music decreased reading comprehension scores, but only for students who seldom study with music. In contrast to this, Johansson et al. (2012) found that participants had lower comprehension accuracy when listening to non-preferred music, but there was no effect of preferred music. Participants’ studying habits also did not modulate the results. Adding further to the confusion, Perham and Currie (2014) found that both liked and disliked lyrical music is equally disruptive to reading comprehension, although they did not report data on students’ studying habits.

The influence of background music on reading may also be modulated by the acoustic properties of the music. Some factors that have been considered are its informational load (Kiger, 1989), loudness and tempo (Thompson, Schellenberg, & Letnic, 2012), familiarity to participants (Hilliard & Tolin, 1979) and its capability to induce a startle response (Ravaja & Kallinen, 2004). These results are quite interesting in understanding what types of music may cause distraction, although they would benefit from further replication and extensions. In summary, previous studies suggest that certain types of music may be distracting, although a negative effect of background music on reading performance has not been consistently observed.

To summarize the discussion so far, the available evidence, mostly from behavioural measures, suggests that experimental exposure to background noise, speech, and music may disrupt reading comprehension.

* Add new papers to lit review

**Theories of auditory distraction**

One of the earliest theoretical accounts of auditory distraction effects is the *phonological interference* hypothesis. This account is based on Baddeley & Hitch’s (1974; 1994) model of working memory, in which the phonological loop acts as an acoustic store where memories are registered and rehearsed through a process of sub-vocalization. Salamé and Baddeley (1982; 1987; 1989) reported a series of experiments in which they showed that memory for visually presented digits is impaired by unattended speech, but not by unattended acoustic noise. Additionally, a disruption effect was observed even if the speech sound was in a language that participants could not understand (Salamé and Baddeley, 1987). The authors argued that this is because speech sounds automatically gain access to the phonological loop and thus interfere with the encoding of visually presented items. Although this hypothesis is derived from a memory task, Salamé and Baddeley (1989) argued that a similar disruption may also be observed in more complex cognitive tasks such as reading.

Martin et al. (1988) were first to systematically test the phonological disruption hypothesis in a reading comprehension task. In a series of experiments, they found that the disruptive effect of unattended speech was due to the semantic properties (i.e. meaning) of the speech, rather than its phonological features. More specifically, the authors found that English speech (intelligible to participants) was more distracting that Russian speech (unintelligible to participants). Similarly, a continuous speech stream of random words was found to disrupt comprehension more than a continuous speech stream of non-words. To account for these results, Martin et al. (1988) argued that, unlike serial recall tasks, reading comprehension requires understanding the meaning of the text. Therefore, the semantic properties of the irrelevant speech can interfere with building the semantic representations of the text that is being read. This prediction will be referred to as the *semantic interference* hypothesis.

The *changing-state* hypothesis (Hughes & Jones, 2001; Jones & Macken, 1993; Jones, Madden, & Miles, 1992) is another prediction that is also derived from serial recall tasks. According to this hypothesis, interference is caused by background sounds that exhibit considerable acoustic variation, but not by steady-state, aperiodic sounds that do not have such variation (Jones et al., 1992). For example, a sound consisting of different consonants (e.g., “B”, “F”, “P”, “S”, “N”) should cause more interference than a sound made up of the same consonant (e.g., “M, M, M, M, M”) because it exhibits more acoustic variation. The hypothesized mechanism through which interference occurs is that changing-state sounds contain information about the serial order of the constituent sounds (Hughes & Jones, 2001). This information in turn can interfere with maintaining the serial order of items in a memory task.

Although reading may pose different task demands, it also involves maintaining the order of words in the sentence, as well as their syntactic relations. For example, models of parallel word processing such as the SWIFT model (Engbert, Nuthmann, Richter, & Kliegl, 2005) assume, at least implicitly, that readers are somehow able to maintain word-order information while processing multiple words at the same time. Similarly, cue-based retrieval models of sentence comprehension (e.g. ) involve storing syntactic cues about. These cues are by necessity also stored in blah-blah.

A final account that is relevant in a reading task is the *duplex theory* of auditory distraction (Hughes, 2014; Hughes, Vachon, & Jones, 2005; 2007; Sörqvist, 2010a). According to this theory, auditory distraction can occur from two different processes: *interference-by-process* and *attentional capture* (Hughes, 2014). Interference-by-process (Marsh, Hughes, & Jones, 2008; 2009; Marsh & Jones, 2010) occurs when the background sound interferes with a process that is important for the main task. For example, in a reading task, the semantic processing of meaningful speech would interfere with the task because reading also requires semantic processing to extract the meaning of the text. Alternatively, auditory distraction can also be caused by attentional capture (Hughes et al., 2005; Vachon, Hughes, & Jones, 2012) where attention is temporally directed away from the main task. For example, the sound “B” in the sequence “AAAAAA**B**A” would capture attention because another “A” is expected in the sequence (Hughes, 2014).

The present investigation does not make it possible to distinguish between the disruption by process or disruption by process accounts. However, we will return to this issue in the discussion.

Although attentional capture is a very interesting concept, it more difficult to study in longer tasks such as reading that typically involve long exposure to sounds.

1. **Phonological interference** (Salamé, & Baddeley, 1982; 1987; 1989)

Previous studies using a reading comprehension task have provided little or no support for a role in phonology in interference by background speech (Hyönä & Ekholm, 2016, Experiment 1; Martin, Wogalter, & Forlano, 1988; Vasilev, Liversedge, Rowan, Kirkby, & Angele, n.d.).

1. **Semantic interference** (Martin, Wogalter, & Forlano, 1988)
2. **Interference-by-process** (Marsh, Hughes, & Jones, 2009; Marsh & Jones, 2010).
3. **Duplex theory** (attentional capture/ interference process) (Hughes, 2014)
4. **Changing state hypothesis** (Hughes & Jones, 2001; Jones, Madden, & Miles, 1992)- originally developed in serial memory task, which shows ISE. However, it can be argued that reading also involves maintaining serial relationships between words. For example, models of parallel word processing such as SWIFT assume, at least implicitly, that readers are somehow able to maintain word-order information while processing multiple words at the same time.
5. **Predictions**

Since most of the theories outlined above were not originally developed in a reading comprehension task, it is important to note that the present investigation is not a strict test of the theories. Rather, it aims to find out whether, and to what extent, they can accommodate the existing evidence in reading tasks.

Whether the nature of the disruption is content-based or processed-based is beyond the scope of the present investigation. However, we will return to this question in the Discussion.

Because the content of the irrelevant speech is often not related to the content of the text that participants are reading (see for an exception), interference-by-process makes the same prediction as the

**Hypothesis 1 (phonological interference):**

According to the phonological interference account, speech that is completely unintelligible to participants (e.g. in a foreign language) should be just as disruptive as

speech that is intelligible to them (i.e., in their native language).

In its strictest form, the phonological disruption hypothesis would also predict that intelligible speech would be more disruptive than lyrical music. The reason for this is that lyrical music would, on average, contain less speech and therefore less phonological information than a continuous stream of speech.

Comparisons (descriptive/ general purpose):

General (all sound)- acc & speed

General (music)- acc

General (speech)- acc

General (noise)- acc

Theoretical:

* Lyrical vs non-lyrical music (semantic/phonological): argue that phonological contribution is possible; however, several studies so far have failed to provide evidence for a central role of phonology in a reading task
* Lyrical music vs speech (phonological): because on average music contains less phonological information compared to speech (however, both contain semantics/ meaning).
* Changing state hypothesis: acoustic noise (e.g. hissing vs instrumental music). Music will be more variable than random/ white noise; traffic, office etc. noise should be more disruptive by Gaussian/ white noise.
* Attentional capture: think about which sounds would be more attentionally capturing; try to find some references
* Interference by process: noise and (non-lyrical music) vs speech and lyrical music; former should not disrupt reading at all since music/ noise processing is irrelevant

The purest test of the changing-state hypothesis is comparing non-speech steady state sounds (e.g. white noise) to non-speech sounds that show greater acoustical variation (e.g. non-vocal music).

Notes:

Not enough studies for foreign vs native

Although it is sometimes assumed that results from different tasks and cognitive domains may extend to other tasks and domain, this is not necessarily the case.

Citations for: speech is perceived as distracting by office workers (see Haapakangas et al., 2014)

Last few decades have seen the emergence of a broad literature field that has focused on more fundamental skills such as working memory and serial recall. There have been some consistent findings and also theories have been developed to account for these results.

However, more complex cognitive tasks such as reading have received mixed findings. Additionally, it is not known whether findings from simple tasks such as serial recall would generalise to reading. Reading is appealing because it is easier to generalise to everyday tasks- how working memory is used in daily life is more difficult to say.

What we try here is to examine the potential of these theories to explain if, and what types of sounds are distracting during reading. It is necessary to consider theories that make the same predictions and are hard to distinguish from one another based on present findings.

**Present Study**

The inconsistent results raise the question of how much distraction, if any, is incurred in the reading process by different sounds when all the available evidence is taken into account. Bayesian is ideally suited to tackle controversial issues as it directly computes the probability of blah-blah.

* Present study achieved greater control over type of studies that were included: only those with a silence baseline, thus raising confidence in comparisons and overall conlusions regarding reading-specific effects

Bayesian meta-analytical models have traditionally been used in biology and medicine (e.g. Sutton & Abrams, 2001; Sutton et al. 2000), but more recently have also been introduced to psychology and linguistics (Vasishth, 2015; Vasishth, Chen, Li, & Guo, 2013; Jäger, Engelmann, & Vasishth, 2017).

Studies of chronic exposure to noise answer a qualitatively different question and are often confounded by social deprivation and other related variables (citation). Therefore, only studies that experimentally manipulated the background sound condition were considered.

Although noise et al. meta-analyses spanning a wide range of behavioural and cognitive tasks are impressive and interesting in their own right, they are not very informative about specific tasks such as reading. Also, existing meta-analyses are quickly becoming outdated. Music meta- confounds of statistical independence and surprising effect that cognitive ES is 0.

Bayesian meta-analysis methods are especially useful in addressing controversial findings or research areas where there are a small number of studies or a lot of uncertainty in the effects.

**Method**

**Literature Search**

The search of the literature was conducted by following the PRISMA guidelines (Moher, Liberati, Tetzlaff, Altman, & Prisma Group, 2009). A flowchart of the process is presented in Figure 1. Google Scholar, Scopus, the Web of Science, and ProQuest Dissertations were searched with the following keywords: “background noise AND reading”, “background speech AND reading”, “background music AND reading”. The search for each of the three background sounds was done separately. The literature search covered articles published before the 25th of June, 2017. Additionally, the reference lists of all screened articles and those of previous literature reviews and meta-analyses on similar topics (Beaman, 2005; Clark & Sörqvist, 2012; Dalton, & Behm, 2007; Kämpfe, Sedlmeier, & Renkewitz, 2010; Klatte, Bergström, & Lachmann, 2013; Shield & Dockrell, 2003; Szalma & Hancock, 2011) were also examined. The identified articles were evaluated against the inclusion criteria presented in Appendix A. In short, the studies had to experimentally manipulate background noise, speech or music in a reading or a proofreading task, have a sound methodological design, and include reading in silence as a baseline condition. The inclusion criteria were developed prior to the meta-analysis with the help of a smaller, qualitative review of the literature. Overall, xx % of the experiments whose eligibility was assessed were included in the meta-analysis. Although the inclusion rate may appear to be low, it was necessary to ensure that only studies that are similar enough to be analyzed together are included. Information about the included studies and their effect sizes are presented in Appendix B.

C:\Users\mvasilev\Dropbox\PhD\Noise\reading_sounds\Literature_search\flowchart.tif

*Figure 1*. A flowchart illustrating the stages of the literature search process.

**Dependent Measures**

Although experiments with a proofreading task were also included, the results from such studies were analyzed separately from studies from reading comprehension task (xx %)

**Effect Size Calculation**

* Make it clear silence was the control here

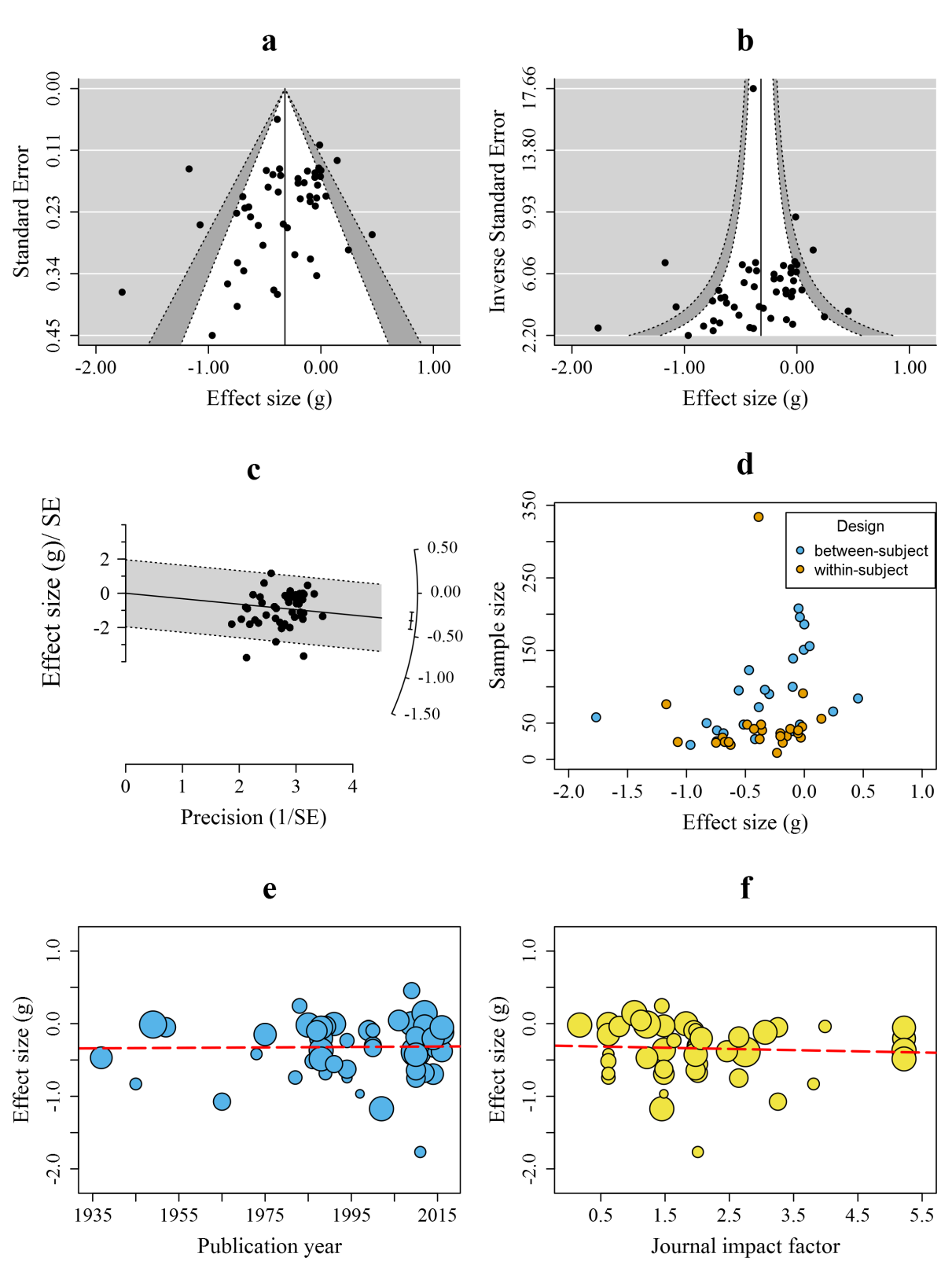
Standardized effect sizes of the mean difference were calculated from the reported descriptive statistics by first calculating Cohen’s *d* and then applying Hedges’ *g* (Hedges & Olkin, 1985) correction for small sample bias. This was done using formulas 12.11-12.22 from Borenstein (2009). If descriptive statistics were unavailable or incomplete, the effect sizes were calculated by digitalizing graphs (Rohatgi, 2015) or converted/approximated from the reported test statistics by using existing formulas (Borenstein, 2009; Lajeunesse, 2013). In the analysis of reading comprehension accuracy and proofreading accuracy, studies were coded so that negative effect sizes indicate lower comprehension accuracy in the experimental sound conditions. Similarly, in the analysis of reading speed, negative effect sizes also indicate slower reading speed in the experimental sound conditions.

Due to the fact that 55.5% of the studies used a within-subject design, it was necessary to estimate the population correlation (ρ) between the control and experimental conditions. (Borenstein, 2009; Szalma & Hancock, 2011). Eight statistically-independent estimates were obtained from experiments for which the raw data were available, as well as from one study (Miller, 1947) that reported the required statistics. These represented a wide range of experimental sound types and included both reading comprehension and reading speed measures. We followed Szalma and Hancock’s (2011) approach to meta-analyze the obtained correlations and to obtain a weighted estimate of ρ. The resulting weighted value of 0.74 was used for calculating the effect sizes for within-subject design studies.

**Publication Bias**

In the present meta-analysis, 12.3% of the included studies were from the so-called grey literature (i.e. they were not formally published in a peer-reviewed journal or in an edited book at the time of analysis).

A test of funnel plot asymmetry based on a weighted linear regression of the effect estimates on their standard errors (Sterne et al., 2011) indicated no statistically significant evidence for asymmetry for both reading comprehension () and reading speed ().



*Figure x*. Visual assessment of publication and related biases for reading comprehension accuracy (presentation format adapted from Nakagawa, Noble, Senior, & Lagisz, 2017, Figure 6). **a** White and dark grey bounds indicate respectively 95% and 99% pseudo-confidence intervals.

**Data Analysis**

A random-effects meta-analysis model was chosen a priori because some between-study heterogeneity was expected and because this model makes more

Let T\_i denote the observed standardized effect size (in Hedges’ g) in the *i*-th study, where *i* ranged from 1, 2, 3, ..., n

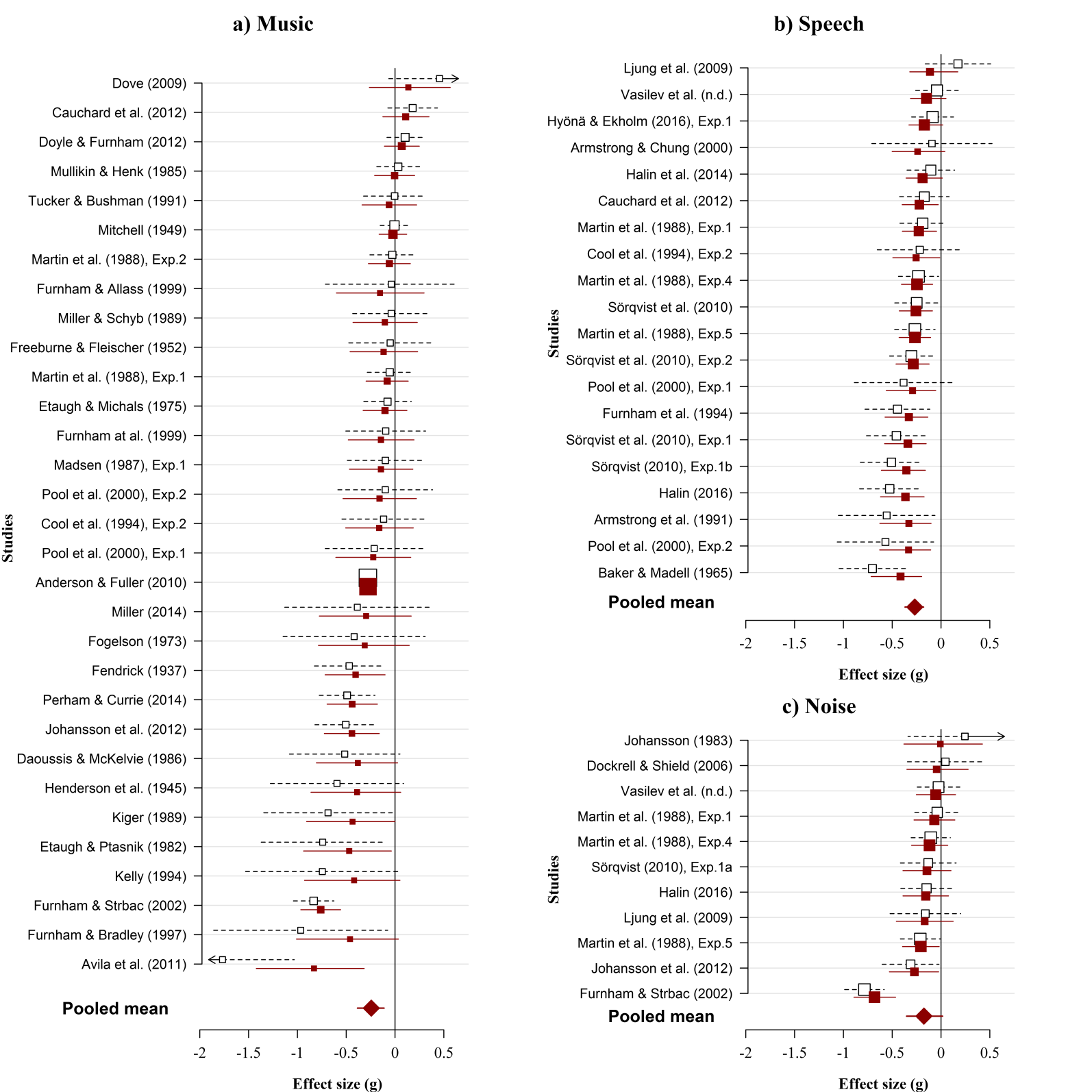
Add a table with the meta-regression contrasts.

The posterior probability distribution from the analyses was sampled with JAGS (Plummer, 2003) using the R software, v. 3.31 (R Core Team, 2016). Five Markov Chain Monte Carlo (MCMC) chains were run with 75 000 iterations each. Checks were made to ensure that the starting values of the MCMC chains did not influence the results. The first 3000 iterations were discarded as burn-in. The MCMC chains were thinned by a factor of 5 (i.e., every fifth iteration was retained) to reduce the influence of auto-correlation. Therefore, the summary of the posterior distribution was based on 12 000 iterations per chain (excluding the burn-in period). Convergence was assessed with visual inspection of the trace plots and by applying Gelman and Rubin’s (1992) convergence diagnostic. The diagnostics suggested that convergence had been achieved in all models.

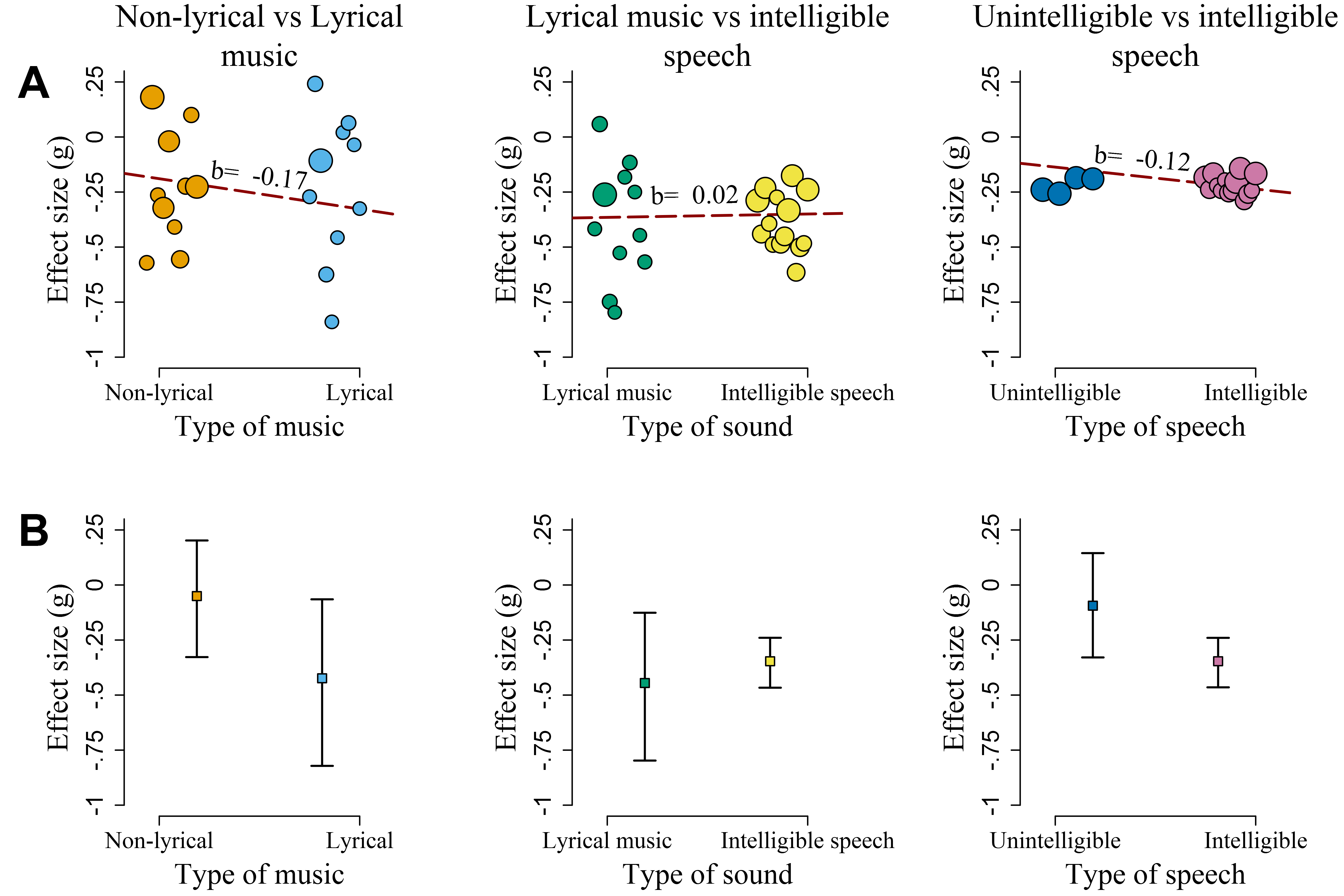
The results are presented as the estimate of the effect sizes of interest and their corresponding 95 % credible intervals. Unlike the classical confidence intervals, credible intervals have the intuitive interpretation that they contain the true parameter with 95% probability because the values within this interval make up 95% of the posterior distribution (Morey, Hoekstra, Rouder, Lee, & Wagenmakers, 2016). In the meta-regression model, All probabilities reported in the paper are the posterior probability, given the data, that the effect of interest exists. A more detailed summary of Bayesian analyses and their interpretation is beyond the scope of this paper. However, а recent paper by Nicenboim and Vasishth (2016) provides an excellent and accessible overview.

**Results**

**Meta-analysis**

*****Figure x*. Forest plot for the main effect of background music (**a**), speech (**b**), and noise (**c**) on reading comprehension. Dark red squares and error bars show the posterior estimate of the study effect from the meta-analysis model and the corresponding 95% CrIs. Open squares and dashed error bars show the observed (i.e. empirical) effect size and the 95% CIs. The size of the squares is proportional to the weight of each study (i.e., the inverse of the variance of the sampling distribution). The pooled estimate from the meta-analysis is shown by the dark red diamond at the bottom of each panel (with 95% CrIs).

**Meta-regression**



*Figure x*. Results of the meta-regression models testing the predictions of semantic and/or phonological disruption hypotheses. Panel **A** shows the regression slope and the studies included the in the analysis. The slope indicates the estimated mean difference (in terms of Hedges’s g) between the two groups. The size of circles is proportional to the weight of individual studies (inverse of the variance of the sampling distribution). Panel **B** shows the posterior effect size for each group, as estimated by a meta-analysis of the simple effect. Error bars show the 95% credible intervals.

Mention that meta-regression results are adjusted for the precision of individual studies.

**Discussion**

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**Appendix A**

**Study Inclusion Criteria**

* The study investigated the effect of experimental exposure to background noise, speech, or music in a reading/ proofreading task.
* Only studies investigating the immediate effect of background sounds on reading/ proofreading were included. Experiments that studied the effect of long-term exposure to music as an intervention for reading were excluded. Studies that investigated the effects of chronic exposure to traffic noise were also excluded.
* The study contained a condition of reading in silence. This served as the baseline to which background sound manipulations were compared. Studies without a silence baseline were excluded.
* The study had appropriate randomization and counter-balancing of the sound conditions.
* Participants were native speakers of the language in which they were reading.
* The study was done with healthy, typically-developing participants (either children or adults).
* The external environment or any additional manipulations did not introduce confounds.
* Participants were not tested on the contents of the sound that they were listening to (e.g. speech).
* The assessment task emphasized comprehension of the text rather than reproducing the text from memory as accurately as possible.
* The comprehension assessment did not occur too long after the reading phase (usually within 10-15 minutes).
* The comprehension assessment was not done under conditions of noise, speech, or music.

**Appendix B**

Table B1

*A Summary of the Studies and Their Effect Sizes That Were Included in the Meta-analysis*

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ID | Study | NC | NE | Sample | Design | DV | Sound | Sound type | dB(A) | g | var |
| 1 | Sörqvist et al. 2010 | 40 | | adults | within | RC | speech | native | 72.5 |  |  |
| 1 | Sörqvist et al. 2010 | 40 | | adults | within | RS | speech | native | 72.5 |  |  |
| 2 | Ljung et al. 2009 | 70 | 50 | children | between | RC | noise | traffic | 62 |  |  |
| 2 | Ljung et al. 2009 | 70 | 50 | children | between | RS | noise | traffic | 62 |  |  |
| 2 | Ljung et al. 2009 | 70 | 66 | children | between | RC | speech | babble | 62 |  |  |
| 2 | Ljung et al. 2009 | 70 | 66 | children | between | RS | speech | babble | 62 |  |  |
| 3 | Fogelson 1973 | 14 | 14 | children | between | RC | music | pop | - |  |  |
| 4 | Tucker & Bushman 1991 | 75 | 76 | adults | between | RC | music | rock & roll | 80 |  |  |
| 5 | Daoussis & McKelvie 1986 | 24 | 24 | adults | between | RC | music | rock | 50 |  |  |
| 6 | Etaugh & Michals 1975 | 32 | | adults | within | RC | music | preferred | - |  |  |
| 7 | Etaugh & Ptasnik 1982 | 20 | 20 | adults | between | RC | music | preferred | - |  |  |
| 8 | Kiger 1989 | 18 | 18 | children | between | RC | music | low load | - |  |  |
| 8 | Kiger 1989 | 18 | 18 | children | between | RC | music | high load | - |  |  |
| 9 | Miller & Schyb 1989 | 49 | 49 | adults | between | RC | music | classical | 47.5 |  |  |
| 9 | Miller & Schyb 1989 | 49 | 49 | adults | between | RC | music | pop | 47.5 |  |  |
| 9 | Miller & Schyb 1989 | 49 | 49 | adults | between | RC | music | vocal | 47.5 |  |  |
| 10 | Doyle & Furnham 2012 | 56 | | adults | within | RC | music | vocal | - |  |  |
| 11 | Anderson & Fuller 2010 | 334 | | children | within | RC | music | lyrical | 75 |  |  |
| 12 | Furnham & Strbac 2002 | 76 | | children | within | RC | noise | office | - |  |  |
| 12 | Furnham & Strbac 2002 | 76 | | children | within | RC | music | vocal/unfam. | - |  |  |
| 13 | Mullikin & Henk 1985 | 45 | | children | within | RC | music | classical | - |  |  |
| 13 | Mullikin & Henk 1985 | 45 | | children | within | RC | music | rock | - |  |  |
| 14 | Avila et al. 2011 | 19 | 20 | children | between | RC | music | vocal/ familiar | - |  |  |
| 14 | Avila et al. 2011 | 19 | 19 | children | between | RC | music | Instr./ familiar | - |  |  |
| 15 | Freeburne & Fleisch. 1952 | 43 | 46 | adults | between | RC | music | classical | - |  |  |
| 15 | Freeburne & Fleisch. 1952 | 43 | 46 | adults | between | RS | music | classical | - |  |  |
| 15 | Freeburne & Fleisch. 1952 | 43 | 42 | adults | between | RC | music | pop | - |  |  |
| 15 | Freeburne & Fleisch. 1952 | 43 | 42 | adults | between | RS | music | pop | - |  |  |
| 15 | Freeburne & Fleisch. 1952 | 43 | 40 | adults | between | RC | music | semi-classical | - |  |  |
| 15 | Freeburne & Fleisch. 1952 | 43 | 40 | adults | between | RS | music | semi-classical | - |  |  |
| 15 | Freeburne & Fleisch. 1952 | 43 | 37 | adults | between | RC | music | jazz | - |  |  |
| 15 | Freeburne & Fleisch. 1952 | 43 | 37 | adults | between | RS | music | jazz | - |  |  |
| 16 | Fendrick 1937 | 61 | 62 | adults | between | RC | music | semi-classical | - |  |  |
| 17 | Henderson et al. 1945 | 19 | 17 | adults | between | RC | music | classical | - |  |  |
| 17 | Henderson et al. 1945 | 19 | 14 | adults | between | RC | music | pop | - |  |  |
| 18 | Miller 2014 | 13 | 13 | adults | between | RC | music | classical lyrical | - |  |  |
| 18 | Miller 2014 | 13 | 17 | adults | between | RC | music | classical instr. | - |  |  |
| 18 | Miller 2014 | 13 | 11 | adults | between | RC | music | rock lyrical | - |  |  |
| 18 | Miller 2014 | 13 | 18 | adults | between | RC | music | rock instr. | - |  |  |
| 19 | Furnham & Allass 1999 | 16 | 16 | adults | between | RC | music | complex | - |  |  |

Table B1 (continued)

*A Summary of the Studies and Their Effect Sizes That Were Included in the Meta-analysis*

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ID | Study | NC | NE | Sample | Design | DV | Sound | Sound type | dB(A) | g | var |
| 19 | Furnham & Allass 1999 | 16 | 16 | adults | between | RC | music | simple | - |  |  |
| 20 | Furnham & Bradley 1997 | 10 | 10 | adults | between | RC | music | pop | - |  |  |
| 21 | Furnham at al. 1999 | 43 | 49 | children | between | RC | music | instrumental | - |  |  |
| 21 | Furnham at al. 1999 | 43 | 47 | children | between | RC | music | vocal | - |  |  |
| 22 | Perham & Currie 2014 | 30 | | adults | within | RC | music | disliked lyrical | 70 |  |  |
| 22 | Perham & Currie 2014 | 30 | | adults | within | RC | music | non-lyrical | 70 |  |  |
| 22 | Perham & Currie 2014 | 30 | | adults | within | RC | music | liked lyrical | 70 |  |  |
| 23 | Kelly 1994 | 13 | 12 | adults | between | RC | music | pop | 65 |  |  |
| 24 | Dove 2009 | 28 | 28 | adults | between | RC | music | sedat. classical | 62.5 |  |  |
| 24 | Dove 2009 | 28 | 28 | adults | between | RC | music | stimul. classical | 62.5 |  |  |
| 24 | Dove 2009 | 28 | 28 | adults | between | RS | music | sedat. classical | 62.5 |  |  |
| 24 | Dove 2009 | 28 | 28 | adults | between | RS | music | stimul. classical | 62.5 |  |  |
| 25 | Furnham et al. 1994 | 20 | | adults | within | RC | speech | TV drama | - |  |  |
| 26 | Johansson 1983 | 22 | 22 | children | between | RC | noise | continuous | 51 |  |  |
| 26 | Johansson 1983 | 22 | 22 | children | between | RC | noise | intermittent | 67.4 |  |  |
| 27 | Halin 2016 | 28 | | adults | within | RC | speech | native (easy) | 60 |  |  |
| 27 | Halin 2016 | 28 | | adults | within | RC | speech | native (diff) | 60 |  |  |
| 27 | Halin 2016 | 28 | | adults | within | RC | noise | traffic (easy) | 60 |  |  |
| 27 | Halin 2016 | 28 | | adults | within | RC | noise | traffic (diff) | 60 |  |  |
| 27 | Halin 2016 | 28 | | adults | within | RC | noise | aircraft (easy) | 60 |  |  |
| 27 | Halin 2016 | 28 | | adults | within | RC | noise | aircraft (diff) | 60 |  |  |
| 28 | Smith-Jacks. & Klein 2009 | 54 | | adults | within | PR | speech | native | 65 |  |  |
| 29 | Cauchard et al. 2012 | 30 | | adults | within | RC | music | instrumental | 65 |  |  |
| 29 | Cauchard et al. 2012 | 30 | | adults | within | RC | speech | native | 65 |  |  |
| 29 | Cauchard et al. 2012 | 30 | | adults | within | RS | music | instrumental | 65 |  |  |
| 29 | Cauchard et al. 2012 | 30 | | adults | within | RS | speech | native | 65 |  |  |
| 30 | Johansson et al. 2012 | 24 | | adults | within | RC | music | preferred | 65 |  |  |
| 30 | Johansson et al. 2012 | 24 | | adults | within | RC | music | non-preferred | 65 |  |  |
| 30 | Johansson et al. 2012 | 24 | | adults | within | RC | noise | cafe | 65 |  |  |
| 30 | Johansson et al. 2012 | 24 | | adults | within | RS | music | preferred | 65 |  |  |
| 30 | Johansson et al. 2012 | 24 | | adults | within | RS | music | non-preferred | 65 |  |  |
| 30 | Johansson et al. 2012 | 24 | | adults | within | RS | noise | cafe | 65 |  |  |
| 31 | Weinstein 1974 | 15 | 18 | adults | between | PR† | noise | teletype | 70 |  |  |
| 31 | Weinstein 1974 | 15 | 18 | adults | between | PR‡ | noise | teletype | 70 |  |  |
| 32 | Weinstein 1977 | 29 | | adults | within | PR† | speech | native | 68 |  |  |
| 32 | Weinstein 1977 | 29 | | adults | within | PR‡ | speech | native | 68 |  |  |
| 33 | Martin et al. 1988, Exp.1 | 36 | | adults | within | RC | speech | native | 82 |  |  |
| 33 | Martin et al. 1988, Exp.1 | 36 | | adults | within | RC | speech | random | 82 |  |  |
| 33 | Martin et al. 1988, Exp.1 | 36 | | adults | within | RC | music | instrumental | 82 |  |  |
| 33 | Martin et al. 1988, Exp.1 | 36 | | adults | within | RC | music | random tones | 82 |  |  |
| 33 | Martin et al. 1988, Exp.1 | 36 | | adults | within | RC | noise | white | 82 |  |  |
| 34 | Martin et al. 1988, Exp.2 | 36 | | adults | within | RC | music | instrumental | 82 |  |  |
| 34 | Martin et al. 1988, Exp.2 | 36 | | adults | within | RC | music | lyrical | 82 |  |  |
| 35 | Martin et al. 1988, Exp.4 | 48 | | adults | within | RC | noise | white | 82 |  |  |

Table B1 (continued)

*A Summary of the Studies and Their Effect Sizes That Were Included in the Meta-analysis*

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ID | Study | NC | NE | Sample | Design | DV | Sound | Sound type | dB(A) | g | var |
| 35 | Martin et al. 1988, Exp.4 | 48 | | adults | within | RC | speech | native | 82 |  |  |
| 35 | Martin et al. 1988, Exp.4 | 48 | | adults | within | RC | speech | foreign | 82 |  |  |
| 36 | Martin et al. 1988, Exp.5 | 48 | | adults | within | RC | noise | white | 82 |  |  |
| 36 | Martin et al. 1988, Exp.5 | 48 | | adults | within | RC | speech | non-word | 82 |  |  |
| 36 | Martin et al. 1988, Exp.5 | 48 | | adults | within | RC | speech | random words | 82 |  |  |
| 37 | Cool et al. 1994, Exp.2 | 9 | | children | within | RS | music | radio/ generic | - |  |  |
| 37 | Cool et al. 1994, Exp.2 | 9 | | children | within | RS | speech | movies | - |  |  |
| 37 | Cool et al. 1994, Exp.2 | 9 | | children | within | RC | music | radio/ generic | - |  |  |
| 37 | Cool et al. 1994, Exp.2 | 9 | | children | within | RC | speech | movies | - |  |  |
| 38 | Mitchell 1949 | 91 | | children | within | RTS | music | radio/ generic | - |  |  |
| 39 | Armstrong et al. 1991 | 33 | 30 | adults | between | RTS | speech | TV ads | - |  |  |
| 39 | Armstrong et al. 1991 | 33 | 32 | adults | between | RTS | speech | TV drama | - |  |  |
| 40 | Pool et al. 2000, Exp.1 | 30 | 30 | children | between | RC | speech | TV soap opera | 60 |  |  |
| 40 | Pool et al. 2000, Exp.1 | 30 | 30 | children | between | RC | music | TV music | 60 |  |  |
| 40 | Pool et al. 2000, Exp.1 | 30 | 30 | children | between | RS | speech | TV soap opera | 60 |  |  |
| 40 | Pool et al. 2000, Exp.1 | 30 | 30 | children | between | RS | music | TV music | 60 |  |  |
| 41 | Pool et al. 2000, Exp.2 | 48 | 24 | children | between | RC | speech | TV soap opera | 60 |  |  |
| 41 | Pool et al. 2000, Exp.2 | 48 | 24 | children | between | RC | music | TV music | 60 |  |  |
| 41 | Pool et al. 2000, Exp.2 | 48 | 48 | children | between | RS | speech | TV soap opera | 60 |  |  |
| 41 | Pool et al. 2000, Exp.2 | 48 | 48 | children | between | RS | music | TV music | 60 |  |  |
| 42 | Dockrell & Shield 2006 | 52 | 52 | children | between | RTS | noise | babble | 65 |  |  |
| 42 | Dockrell & Shield 2006 | 52 | 52 | children | between | RTS | noise | babble+environ. | 65 |  |  |
| 43 | Hyönä & Ekh. 2016, Exp.1 | 42 | | adults | within | RC | speech | native | 82.5 |  |  |
| 43 | Hyönä & Ekh. 2016, Exp.1 | 42 | | adults | within | RC | speech | foreign | 82.5 |  |  |
| 43 | Hyönä & Ekh. 2016, Exp.1 | 42 | | adults | within | RS | speech | native | 82.5 |  |  |
| 43 | Hyönä & Ekh. 2016, Exp.1 | 42 | | adults | within | RS | speech | foreign | 82.5 |  |  |
| 44 | Hyönä & Ekh. 2016, Exp.2 | 36 | | adults | within | RS | speech | scrambl.-differ. | 82.5 |  |  |
| 44 | Hyönä & Ekh. 2016, Exp.2 | 36 | | adults | within | RS | speech | scrambl.-same | 82.5 |  |  |
| 45 | Hyönä & Ekh. 2016, Exp.3 | 35 | | adults | within | RS | speech | native | 82.5 |  |  |
| 45 | Hyönä & Ekh. 2016, Exp.3 | 35 | | adults | within | RS | speech | scrambled | 82.5 |  |  |
| 46 | Hyönä & Ekh. 2016, Exp.4 | 36 | | adults | within | RS | speech | scrambled-sem. | 82.5 |  |  |
| 46 | Hyönä & Ekh. 2016, Exp.4 | 36 | | adults | within | RS | speech | scrm-syn+sem | 82.5 |  |  |
| 47 | Armstrong & Chung 2000 | 19 | 20 | adults | between | RC | speech | native | - |  |  |
| 48 | Madsen 1987, Exp.1 | 50 | 50 | adults | between | RC | music | various | 75 |  |  |
| 49 | Sörqvist 2010, Exp.1a | 23 | | children | within | RC | noise | aircraft | 57.5 |  |  |
| 50 | Sörqvist 2010, Exp.1b | 23 | | children | within | RC | speech | native | 57.5 |  |  |
| 51 | Sörqvist et al. 2010, Exp.1 | 24 | | adults | within | RC | speech | native | 65 |  |  |
| 52 | Sörqvist et al. 2010, Exp.2 | 42 | | adults | within | RC | speech | native | 65 |  |  |
| 53 | Halin et al. 2014 | 32 | | adults | within | RC | speech | native | 65 |  |  |
| 54 | Halin et al. 2014, Exp.1 | 31 | | adults | within | PR‡ | speech | native | 65 |  |  |
| 54 | Halin et al. 2014, Exp.1 | 31 | | adults | within | PR† | speech | native | 65 |  |  |
| 55 | Halin et al. 2014, Exp.2 | 29 | | adults | within | PR‡ | speech | native | 65 |  |  |
| 55 | Halin et al. 2014, Exp.2 | 29 | | adults | within | PR† | speech | native | 65 |  |  |
| 56 | Haapakangas et al. 2011 | 54 | | adults | within | PR‡ | speech | native | 48 |  |  |

Table B1 (continued)

*A Summary of the Studies and Their Effect Sizes That Were Included in the Meta-analysis*

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ID | Study | NC | NE | Sample | Design | DV | Sound | Sound type | dB(A) | g | var |
| 56 | Haapakangas et al. 2011 | 54 | | adults | within | PR† | speech | native | 48 |  |  |
| 56 | Haapakangas et al. 2011 | 54 | | adults | within | PRS | speech | native | 48 |  |  |
| 57 | Baker & Madell 1965 | 24 | | adults | within | RC | speech | native | - |  |  |
| 58 | Vasilev et al. n.d. | 40 | | adults | within | RC | noise | speech-spectr. | 60 |  |  |
| 58 | Vasilev et al. n.d. | 40 | | adults | within | RC | speech | foreign | 60 |  |  |
| 58 | Vasilev et al. n.d. | 40 | | adults | within | RC | speech | native | 60 |  |  |
| 58 | Vasilev et al. n.d. | 40 | | adults | within | RS | noise | speech-spectr. | 60 |  |  |
| 58 | Vasilev et al. n.d. | 40 | | adults | within | RS | speech | foreign | 60 |  |  |
| 58 | Vasilev et al. n.d. | 40 | | adults | within | RS | speech | native | 60 |  |  |
| 59 | Falcon (2017), Sample 1 | 22 | 20 | children | between | RC | music | classical | 55 |  |  |
| 60 | Falcon (2017), Sample 2 | 25 | 28 | children | between | RC | music | classical | 55 |  |  |
| 61 | Ahuja (2016) | 20 | | adults | within | RC | music | liked | 60 |  |  |
| 61 | Ahuja (2016) | 20 | | adults | within | RC | music | disliked | 60 |  |  |
| 62 | Kou et al. (2017) | 31 | 29 | adults | between | RC | music | pop (vocal) | 65 |  |  |
| 62 | Kou et al. (2017) | 31 | 32 | adults | between | RC | noise | office | 65 |  |  |
| 63 | Sukowski et al. (2016) | 12 | | adults | within | RC | speech | native | 59.5 |  |  |
| 64 | Yan et al. (2017) | 42 | | adults | within | RS | speech | native | 62 |  |  |
| 64 | Yan et al. (2017) | 42 | | adults | within | RS | speech | meaningless | 62 |  |  |

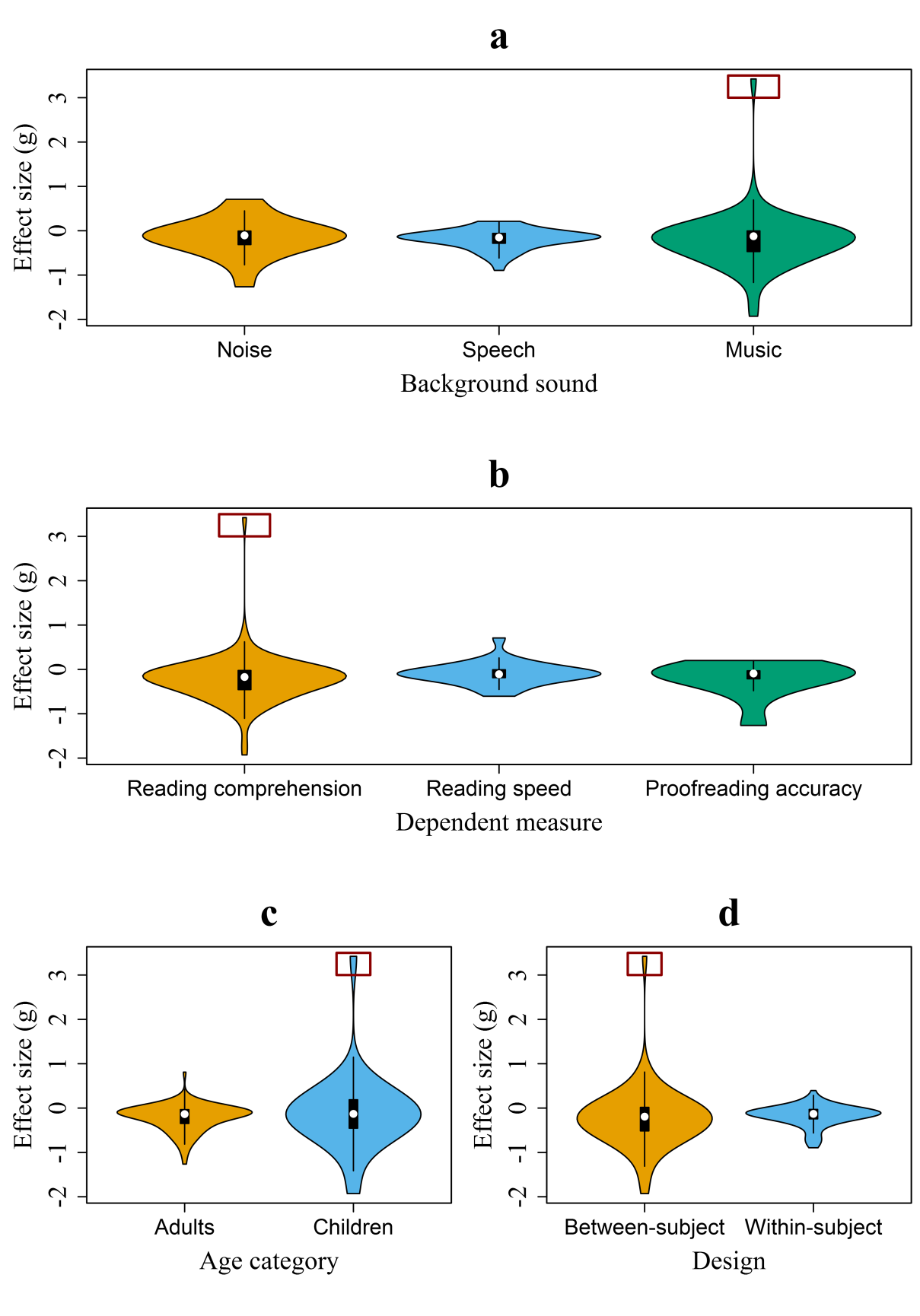
*Note*: NC: number of participants in the control (silence) condition. NE: number of participants in the experimental (sound) condition. RC: Reading comprehension. RS: reading speed. RTS: Reading test score. PR: Proofreading accuracy. ES: Effect size in Hedges’ g.

† Non-contextual errors (proofreading accuracy)

‡Contextual errors (proofreading accuracy)

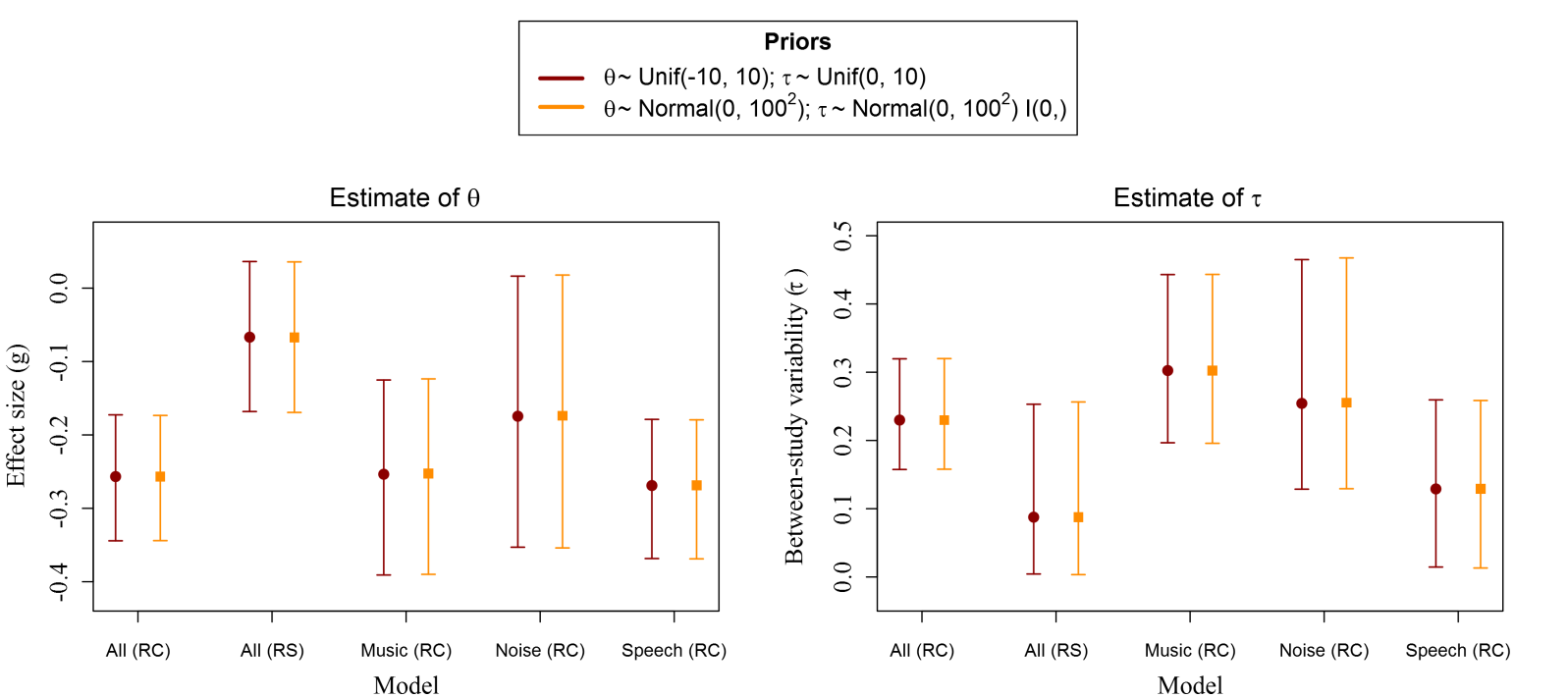
Supplemental Material

**Visualization of Effect Sizes**

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*Figure Sx*. Box plots and probability densities of the effect sizes included in the meta-analysis. Breakdown shown by: background sound type (panel **a**), dependent measure (panel **b**), age of participants (panel **c**), and study design (panel **d**). Red rectangle shows the one effect size that was excluded as an outlier.

**Prior Sensitivity Analysis**



*Figure Sx*. Sensitivity analysis with different priors on the θ and τ parameters for the main meta-analysis results. Uniform priors (dark red) were used in the analysis reported in the main paper. The results show that using diffuse normal priors did not change the main results reported in the paper. All: all studies. RC: reading comprehension. RS: reading speed.

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