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

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.

Max 200 words

*Keywords*: reading, background noise, speech, music, meta-analysis

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 interesting patterns of results have emerged, the research literature has been undermined by a fair number 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 on some topics, it is currently not well understood what the magnitude of auditory distraction effects is, or even whether they are reliably different from 0.

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 the 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 traffic 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 acoustical 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 the babble and the environmental noise were combined. Using similar sound stimuli, Ljung, Sörqvist, 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 acoustic or environmental 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 suggest 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 can 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 acoustical noise (Haka et al., 2009; Haapakangas et al., 2011; Landström, Söderberg, Kjellberg, & Nordström, 2002). Consistent with this subjective perception, intelligible 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 alone 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 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 intelligible 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 a similar 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 intensity level to Venetjoki et al. (2006), although the speech consisted of random spoken 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).

Most 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, several 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.; Yan, Meng, Liu, He, & Paterson, 2017). One 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 have replicated the disruption effect in comprehension accuracy. It is currently not known why this inconsistency exists, but this raises 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 reliable than the effect of background noise on reading, which has not been consistently replicated. Nevertheless, several studies in recent years have found no effect of background speech on reading comprehension, which casts doubt on its robustness and generalizability.

**Background music.** Unlike noise and speech, which are usually a nuisance, 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 negatively impact 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 or fixation probabilities.

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 the extroverts’ higher cortical arousal threshold. However, the results from these studies have been mixed. While some studies have found such an interaction between personality trait and background music (Daoussis & McKelvie, 1986; Furnham & Bradley, 1997; Furnham & Strbac, 2002), others have not (Avila et al., 2011; Furnham & Allass, 1999; Furnham et al., 1999; Furnham & Stephenson, 2007; Kou, McClelland, & Furnham, 2017). A number of factors may have led to these inconsistencies, such as the way in which participants were classified as introverts and extroverts, or 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, but a negative effect of background music on reading performance has not been consistently observed.

To summarize the discussion so far, the available evidence suggests that experimental exposure to background noise, speech, and music may disrupt reading performance. The effect of background noise and music appears to be less consistent, with many studies reporting non-significant effects on reading comprehension. Although the effect of background speech on reading appears to be more reliable, several experiments have also failed to find a distraction effect in reading comprehension and proofreading tasks. Therefore, considerable uncertainty exists with respect to the magnitude of these distraction effects and what aspects of background sounds may be responsible for them. One possibility is that only certain acoustical or linguistic properties of background sounds may account for the distraction. We now turn to this possibility by examining existing theories of auditory distraction.

**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 and 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 and rehearsal 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 their constituent sound elements (Hughes & Jones, 2001). This information in turn can interfere with maintaining the serial order of items in a memory task.

Although reading is a more complex cognitive task, 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 SWIFT (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. Additionally, some models of reading comprehension (e.g., Kintsch, 1998) assume that words meanings are combined to form propositions or “idea units” according to their syntactic relationships (Kintsch & Rawson, 2005). Therefore, the forming of these units must also involve establishing the order of words in the sentence and how they relate syntactically to one another.

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; see also Parmentier, 2014 for a review of similar effects due to deviant sounds).

In a reading task, the interference-by-process part of the duplex theory makes the same prediction as the semantic interference hypothesis by Martin et al. (1988) discussed earlier. In Marsh et al.’s (2008, 2009) account, distraction occurs because processing the meaning of the background speech depends on the same process used for extracting the meaning of the text that is being read. In contrast, Martin et al. (1988) assume that it is the semantic properties of the speech that cause the interference. These two very similar views are difficult to disentangle empirically, and since they make the same prediction, we will consider them together in the present analysis. However, we will return to this issue in the discussion. The second part of the duplex theory- attentional capture- is a very interesting concept. However, because tasks such as reading typically involve longer exposure to sounds, it is more difficult to study and will not be considered further in this analysis.

**Present Study**

The review of the literature revealed that background noise, speech, and music may be detrimental to reading performance, but that considerable uncertainty exists as to whether such disruption effects can be consistently observed and what their magnitude is. This uncertainty does not make it possible to make firm conclusions about the experimental effects, nor does it tell us about their real-world significance. Are background sounds reliably disruptive to reading, and is this disruption large enough to be of any practical significance? Additionally, after 80 years of research on the topic, what theoretical conclusions can be made about the types of background sounds that are disruptive to reading?

The present study addressed these questions by performing a Bayesian random-effects meta-analysis of studies investigating experimental exposure to noise, speech, or music in the background. Both studies with adults and children were considered. Bayesian inference is especially suited to answer these questions because it uses the laws of probability to directly quantify the uncertainty of the estimate of auditory distraction effects, given the available evidence. This in turn makes it possible to derive the probability, given the data, that background noise, speech, and music can distract readers from their task. 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). As such, they have been successfully used to address contentious research questions, such as the processing of relative clauses in Chinese (Vasishth et al., 2013), and the extent to which readers can pre-process words in parafoveal vision (Vasilev & Angele, 2017).

There are two available meta-analyses to date that have addressed how background noise and music affect a wide range of behavioural and cognitive tasks (Kämpfe, Sedlmeier, & Renkewitz, 2010; Szalma & Hancock, 2011). While the results from these meta-analyses are quite interesting, their more general focus on all types of cognitive tasks does not make it possible to make firm conclusions about reading in particular. Interestingly, Kämpfe et al. reported a separate analysis of reading-only studies and estimated the general effect of music to be r= -0.11 (d= -0.22). However, this estimate was based on only 8 studies and thus does not include most of the currently available data. Therefore, one of the contributions of the present meta-analysis was to estimate the general effect of background noise, speech, and music on reading, and to calculate the probability, given all the available evidence, that these auditory backgrounds are detrimental to reading performance.

The second and more important goal of the present analysis was to investigate what aspects of background sounds give rise to distraction. Although it can be informative to estimate the overall size of the effects, as previous meta-analyses have, this does not tell us what it is about these sounds that makes them distracting. As it was discussed previously, there are a few theories that make specific predictions about what type of auditory stimuli should be distracting. Therefore, the second aim of the study was to test the prediction of these theories using Bayesian meta-regression models (Welton, Sutton, & Cooper, 2012). As some of the theories outlined above were not originally developed in reading comprehension tasks, it is important to keep in mind that the present investigation is not a strict test of these theories. Rather, it aims to find out whether they can accommodate the existing evidence in reading tasks, and if not, to pave the way for the development of future theories.

**Predictions.** All of the predictions in the present analyses are summarised in Figure 1.The phonological interference hypothesis (Salamé, & Baddeley, 1982) makes the unique prediction that all types of speech should be equally distracting because they all gain access to the phonological store. Therefore, both intelligible speech (i.e., in participants’ native language) and unintelligible speech (i.e., in a foreign language) should be equally distracting. Additionally, the phonological interference hypothesis is not capable of explaining distraction by acoustical noise and non-lyrical music because both sounds do not gain access to the phonological store.

The semantic interference (Martin et al., 1988) and interference-by-process (Marsh et al., 2008) accounts both make the unique prediction that only intelligible speech that can be processed semantically by participants would cause distraction. Therefore, intelligible speech should be more distracting than unintelligible speech. Additionally, they also predict that: 1) lyrical music should be more distracting than non-lyrical music because the former contains lyrics that are intelligible to participants; and 2) intelligible speech should be more distracting than lyrical music because, on average, continuous speech has more semantic content than lyrical music. However, since lyrical music that is intelligible to participants contains not only semantic, but also phonological information, it is not possible to rule out any involvement of phonology in this effect. C:\Users\mvasilev\OneDrive\RSmeta\predictions.tif

*Figure 1*. A schematic summary of the predictions derived from theories on auditory distraction.

Finally, the changing-state hypothesis (Jones et al., 1992) predicts that sounds exhibiting considerable acoustic variation should be more distracting than steady-state sounds that do not exhibit such variation. This leads to a two predictions. First, non-lyrical music should be more distracting than acoustical noise (e.g. white or pink noise). This is because the former exhibits more acoustical variation. Non-lyrical music is the strongest test of this prediction because it avoids any potential confounds from spoken language that would be present in lyrical music. Second, more complex environmental noise (e.g. traffic noise or office noise containing, phones ringing, indistinct chatter, etc.) should again be more distracting that steady-state acoustical noise because it also exhibits more acoustical variation.

**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 2. 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, as well as those of previous literature reviews and meta-analyses on similar topics (Beaman, 2005; Clark & Sörqvist, 2012; Dalton, & Behm, 2007; Kämpfe et al., 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. Epidemiological studies of chronic exposure to traffic noise in children were not included because they answer a qualitatively different question and are often confounded by other variables, such as social deprivation (Haines, Stansfeld, Head, & Job, 2002). Overall, 44 % 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.

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*Figure 2*. A flowchart illustrating the stages of the literature search process.

**Dependent Measures**

The main dependent variable was reading comprehension accuracy, which was available for 54 of the studies (83.1 %). Therefore, most of the reported analyses were based on reading comprehension. Moreover, effect sizes for reading speed were available for 13 studies (20 %), and these were analyzed separately. Finally, experiments reporting proofreading accuracy (N=7; 10.7 %) were also analyzed for completeness, but this was again done separately from the analysis on reading comprehension accuracy.

**Effect Size Calculation**

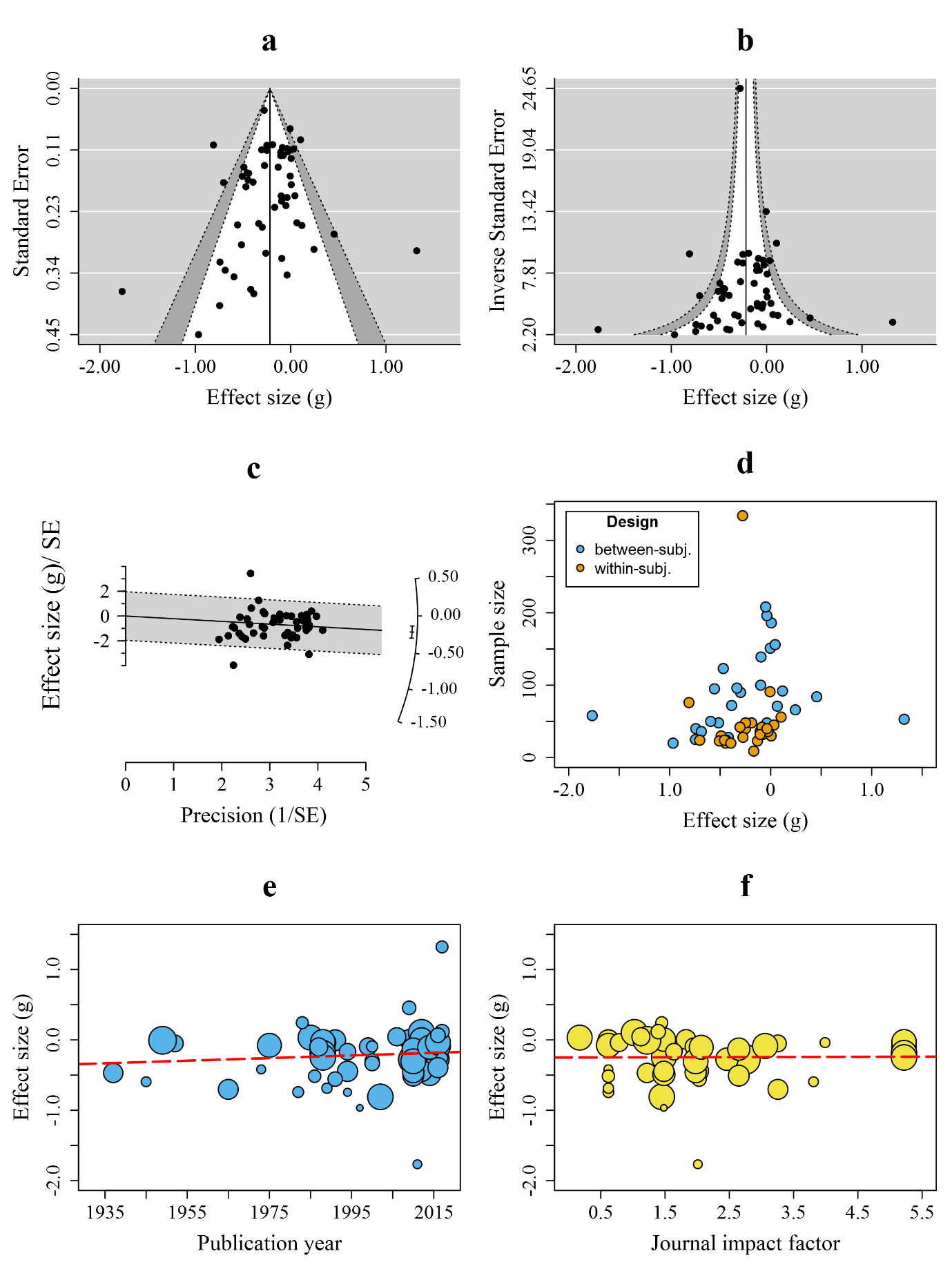
Standardized effect sizes of the mean difference (g) and their variances were calculated from the reported descriptive statistics. This was done by first calculating Cohen’s *d* for the respective design of the study and then applying Hedges’ *g* (Hedges & Olkin, 1985) correction for small sample bias. The effect sizes were calculated with formulas 12.11-12.22 from Borenstein (2009). In all effect sizes, silence was the control condition. Therefore, the effects represent the standardized mean difference between reading in the experimental sound condition and the control condition of reading in silence. 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)[[1]](#footnote-1). In the analysis of reading comprehension accuracy and proofreading accuracy, studies were coded so that negative effect sizes indicate lower comprehension/ proofreading 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 condition compared to silence.

Because 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 all within-subject design studies.

Effect sizes from within- and between-subject studies are calculated with different standard deviation metrics and are thus not necessarily comparable (Morris & DeShon, 2002). Consistent with previous work (Kämpfe et al., 2010; Szalma & Hancock, 2011), the effect sizes from within-subject studies were transformed to make them comparable to the effect sizes of between-subject studies. This was done with formula 11 from Morris and DeShon (2002). Additionally, because some studies yielded more than one effect size, care was taken to avoid statistical non-independence in the analyses (see Noble, Lagisz, O'dea, & Nakagawa, 2017 for a recent overview). If a study contributed multiple effect sizes per analysis, these were averaged together to include only one effect size for that study (Lipsey & Wilson, 2001)[[2]](#footnote-2).

**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). Additionally, we performed visual and statistical investigation of publication and other related biases. This was done with the “meta” (Schwarzer, 2007) and “metaphor” (Viechtbauer, 2010) R packages. The visualization of the results for reading comprehension is presented in Figure 3 (see the Supplemental Material for reading speed). The funnel plots (panels **a** and **b**) indicated that there was some heterogeneity in the data, but there was no clear evidence of asymmetry that could indicate publication bias. This was confirmed by a funnel plot test of asymmetry based on a weighted linear regression of the effect estimates on their standard errors (Sterne et al., 2011), which revealed no statistically significant evidence for asymmetry for either reading comprehension (t(52) = -0.42, p= 0.67) or reading speed (t(11)= 0.08, p= 0.93; proofreading accuracy was not considered here because funnel plot tests of asymmetry are not recommended when there are less than 10 studies; Sterne et al., 2011). Additionally, meta-regression analyses (Figure 3**e**-**f**) indicated that the size of auditory distraction effects was not predicted by the impact factor of the journal or the year of publication. In summary, there was no evidence to suggest that publication bias may have influenced the conclusions from the meta-analysis.

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*Figure 3*. Visual assessment of publication and other related biases for reading comprehension accuracy (presentation format adapted from Nakagawa, Noble, Senior, & Lagisz, 2017, Figure 6). **a**: Funnel plot of effect sizes against their standard error.White and dark grey bounds indicate the 95% and 99% pseudo-confidence intervals, respectively. Studies with smaller standard error should appear at the top, while studies with smaller standard error should scatter at the bottom of the plot. **b**:The same funnel plot of effect sizes against the inverse of the standard error. **c**: Radial (Galbraith) plot of the z-statistic of each study (y axis) against the inverse of the standard error (x axis). Shading shows z-value bounds of ± 2. **d**: Plot of effect sizes against their sample size, broken down by study design type. **e** and **f**: Meta-regression models examining whether the size of effects is predicted by publication year (**e**) or impact factor of the journal where the study was published (**f**). Both models show that this was generally not the case. Red dotted line shows the meta-regression slope.

**Data Analysis**

**Meta-analysis**. The common choice in meta-analysis is between a fixed-effect and a random-effects model. A fixed-effect model assumes that all effect sizes that are combined are estimating the same true underlying effect, which we will call *θ*. Therefore, the effect size of the *i*-th study, *Ti*, is assumed to come from a normal distribution with some mean *θ* and variance :

(1)

In this model, any variability in the estimate is due to sampling error alone. On the other hand, a random-effects model relaxes this assumption by explicitly allowing for variability in the effect sizes between studies (Welton et al., 2012). In this case, the effect size of the *i*-th study *Ti* is assumed to be generated by a unique underlying effect for that study, denoted here by . This unique underlying effect is in turn assumed to come from a normal distribution with some (unknown) mean *θ* and between-study variance *τ2*: (2)

Therefore, the effect sizes of individual studies in a random-effects meta-analysis can be informally thought of as random samples from a normal distribution of effect sizes (Welton et al., 2012).

In the present meta-analysis, a random-effects model was chosen a priori because some between-study heterogeneity was expected due to differences in design, sound intensity levels, participants, reading materials, and so forth. A random-effects model can naturally account for such sources of variability between studies and is often the model of choice in studies on language processing (e.g. Jäger et al., 2017; Vasishth et al., 2013; Vasilev & Angele, 2017). The full Bayesian model was defined as follows (Jäger et al., 2017; Schmid & Mengersen, 2013):   
 (3)

,

,

where: is the observed effect size (in Hedges’ g) in the *i*-th study

is the true auditory distraction effect in the *i*-th study

is the true sampling variance of the *i*-th study, estimated from the within-study variance of the sampling distribution of study *i*

is the unknown true auditory distraction effect estimated by the model

is the unknown between-study variance

In this model, precision was defined as the inverse of the within-study variance of the sampling distribution. The last two lines in equation 3 indicate the prior probability distributions used for *θ* and *τ.* In the present analysis, we used Uniform priors that assign equal probability to any value on these intervals. As such, they have very little to no influence on the results. This was confirmed by doing a sensitivity analysis of the main results with alternative priors: *Normal (0, 104)* for *θ* and *Normal (0, 104) I(0, )* for *τ* (normal distribution truncated at 0)*.* The sensitivity analysis indicated that the choice of priors did not influence the results(see the Supplemental Material).

**Meta-regression**. Although random-effects meta-analysis can account for heterogeneity between studies, it does not tell us what causes this heterogeneity in the first place (Welton et al., 2012). However, it is possible to use meta-regression models to investigate how different study characteristics (e.g. whether the background music was lyrical or non-lyrical) are associated with the observed effect sizes. Meta-regression models are similar to the ordinary least-squares regression, but with the crucial difference that the estimate is adjusted by the precision of the studies (i.e., the inverse of the within-study variance of the sampling distribution; Welton et al., 2012). The model from equation 3 was extended by adding a regression coefficient *β* for the underlying effect of the covariate (the added parameters are formatted in bold; Jäger et al., 2017; Welton et al., 2012):

(4)

,

,

where: *β* is the regression coefficient for the underlying effect of the covariate .

is the true auditory distraction effect in the *i*-th study, adjusted for the covariate effect

is the unknown true auditory distraction effect, also adjusted for the covariate effect

All remaining parameters have the same interpretation as in equation 3.

The contrasts used for the covariate are presented in Table 1. These contrasts were used to test the predictions outlined in the introduction.

Table 1

*Type of Meta-Regression Comparisons and the Contrast Coding of Covariates*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Comparison | Covariate levels | | Contrast coding | |
| Level 1 | Level 2 | Level 1 | Level 2 |
| Non-lyrical vs lyrical music | non-lyrical | lyrical | -1 | 1 |
| Lyrical music vs intelligible speech | music | speech | -1 | 1 |
| Unintelligible vs intelligible speech | unintelligible | intelligible | -1 | 1 |
| Acoustical vs environmental noise | acoustical | environmental | -1 | 1 |
| Acoustical noise vs instrumental music | noise | music | -1 | 1 |
| Child vs adult participants | child | adult | -1 | 1 |

**Posterior sampling.** The posterior probability distribution 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. A thinning interval of 5 was used for the MCMC chains (i.e., every fifth sample was retained) to reduce the influence of auto-correlation. The summary of the posterior distribution was based on 15 000 samples per chain (excluding the burn-in period). Convergence was assessed with visual inspection of the trace plots and with 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 auditory distraction effect with 95% probability because the values within this interval make up 95% of the posterior probability distribution (cf. Morey, Hoekstra, Rouder, Lee, & Wagenmakers, 2016). All probabilities reported in the paper are the posterior probability, given the data, that auditory distraction effects exist. A more detailed summary of Bayesian methods and their interpretation is beyond the scope of this paper. However, Nicenboim and Vasishth (2016) provide an accessible overview.

**Results**

**Meta-analysis**

The results from the meta-analysis are presented in Table 2. Additionally, forest plots are presented in Figure 4 for the main measure of comprehension accuracy. To interpret the magnitude of the effects, we will consider Cohen’s (1988) guidelines of 0.20 for small effects, 0.50 for medium effects, and 0.80 for large effects. Overall, there was a small negative effect for reading comprehension (g= -0.21), which indicates that background sounds generally impaired comprehension accuracy. Consistent with the review of the literature, background speech had a stronger negative impact on reading comprehension (g= -0.26) compared to both background noise and music (g= -0.17 and -0.19, respectively). Nevertheless, the effect for all three sound types was fairly small in size. Reading speed and proofreading accuracy were also impaired by background sounds. However, the effect sizes for these two measures were very small and the 95% credible intervals all included 0 as a plausible value for the effect. Interestingly, however, the probability that these effects are negative was very high in all analyses (more than 90%). This means that, although the size of the effects was small, there was very high probability that background speech, noise, and music are detrimental to reading comprehension, reading speed, and proofreading accuracy.

Table 2

*Posterior Effect Size Estimates of Auditory Distraction Effects and 95% Credible Intervals from the Meta-analysis*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Type of analysis | N | Mean ES (g) | 95% CrI | p(ES<0 | Data) |
| Reading comprehension |  | | | |
| All sounds | 54 | -0.21 | [-0.30, -0.13] | > 0.99 |
| Noise | 12 | -0.17 | [-0.33, 0.002] | 0.97 |
| Speech | 20 | -0.26 | [-0.36, -0.17] | > 0.99 |
| Music | 36 | -0.19 | [-0.34, -0.05] | > 0.99 |
| Reading speed |  | | | |
| All sounds | 13 | -0.06 | [-0.15, 0.02] | 0.92 |
| Speech | 6 | -0.08 | [-0.20, 0.03] | 0.92 |
| Proofreading accuracy |  | | | |
| Speech and Noise | 7 | -0.14 | [-0.42, 0.04] | 0.94 |
| Speech a | 6 | -0.09 | [-0.30, 0.07] | 0.90 |

N: number of studies in the analysis. p(ES<0 | Data): probability that background sounds are distracting, given the data (i.e., probability that the effect size is smaller than 0).

a intelligible speech only

Because both studies with adults and children were included in the analyses above, we carried out meta-regression models to test whether the effect sizes differed between adults and children. Only reading comprehension was considered in these analyses, as there were too few child studies to reliably estimate differences in reading speed, and all proofreading studies were done with adults. The results are presented in Table 3. They show the estimated mean difference between studies with children compared to studies with adults, after adjusting for their precision in the analysis. Overall, the difference between adults and children was very close to 0, thus showing that background sounds were equally detrimental to reading comprehension for both children and adults. One exception was that background noise impaired reading comprehension in children slightly more than it did in adults, but the mean difference was still quite small (g= 0.05). Additionally, the effect was not highly reliable as there was only 74% probability of a true mean difference. Taken together, these results suggest that effect sizes for reading comprehension generally did not differ between adults and children. For this reason, child and adult studies were analyzed together in all remaining analyses.

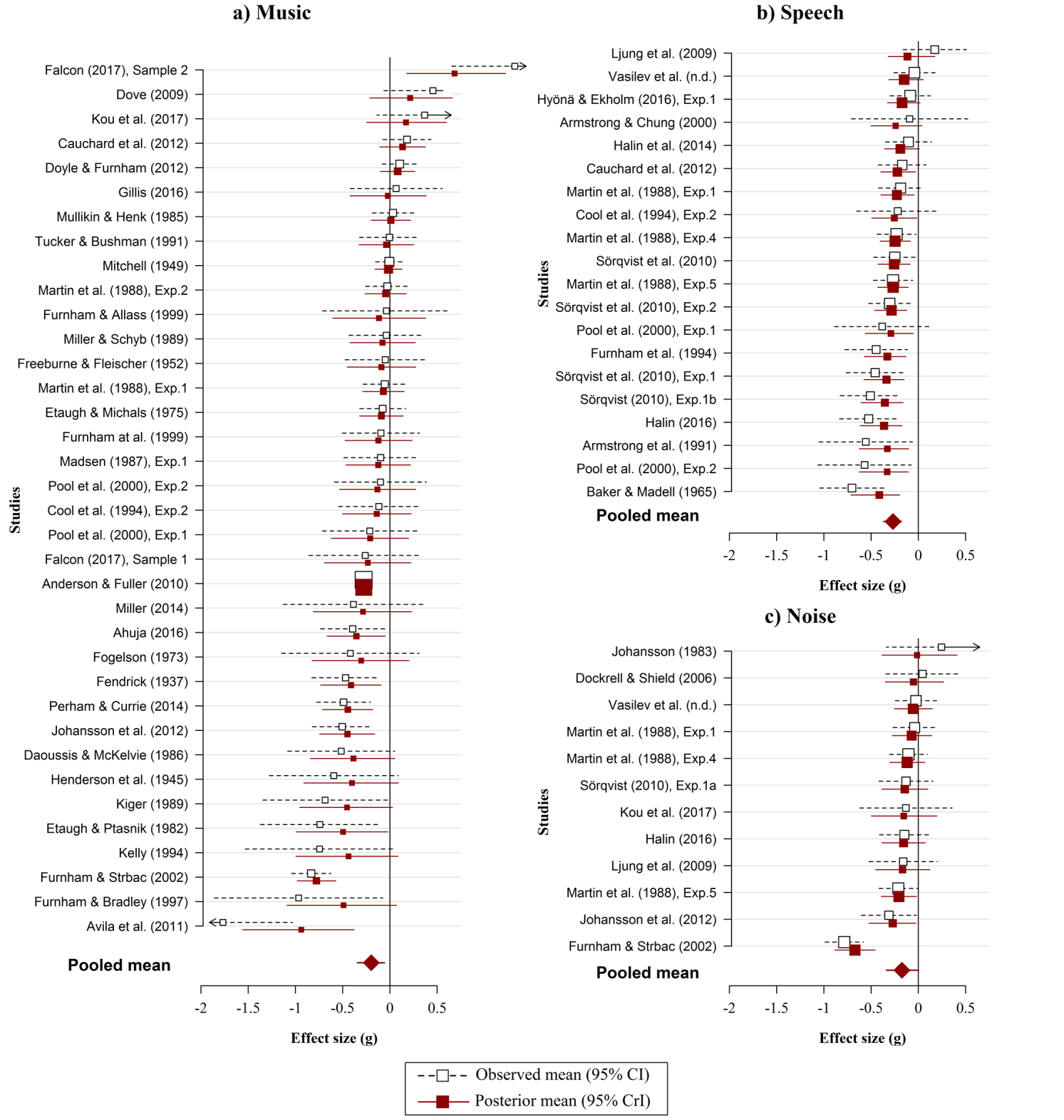


Table 3

*Mean Difference in the Effect Size Between Child and Adult Studies: Meta-regression Results*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Analysis | Number of studies | | Mean diff. (g) | 95 % CrI | p(ESCH> ESA | Data) |
| children | adults |
| Reading comprehension |  | | | | |
| All sounds | 18 | 36 | -0.01 | [-0.10, 0.08] | 0.43 |
| Noise | 5 | 7 | 0.05 | [-0.13, 0.22] | 0.74 |
| Speech | 5 | 15 | 0.00 | [-0.12, 0.12] | 0.51 |
| Music | 13 | 23 | 0.02 | [-0.12, 0.17] | 0.64 |

*Note*: Child studies were coded as -1 and adult studies as 1. Mean diff: Posterior estimate of the mean difference (in Hedges’ g) between adult and child participants. CrI: credible interval. p(ESCH> ESA): probability that the effect sizes for child participants are bigger than the effect sizes for adult participants, given the data.

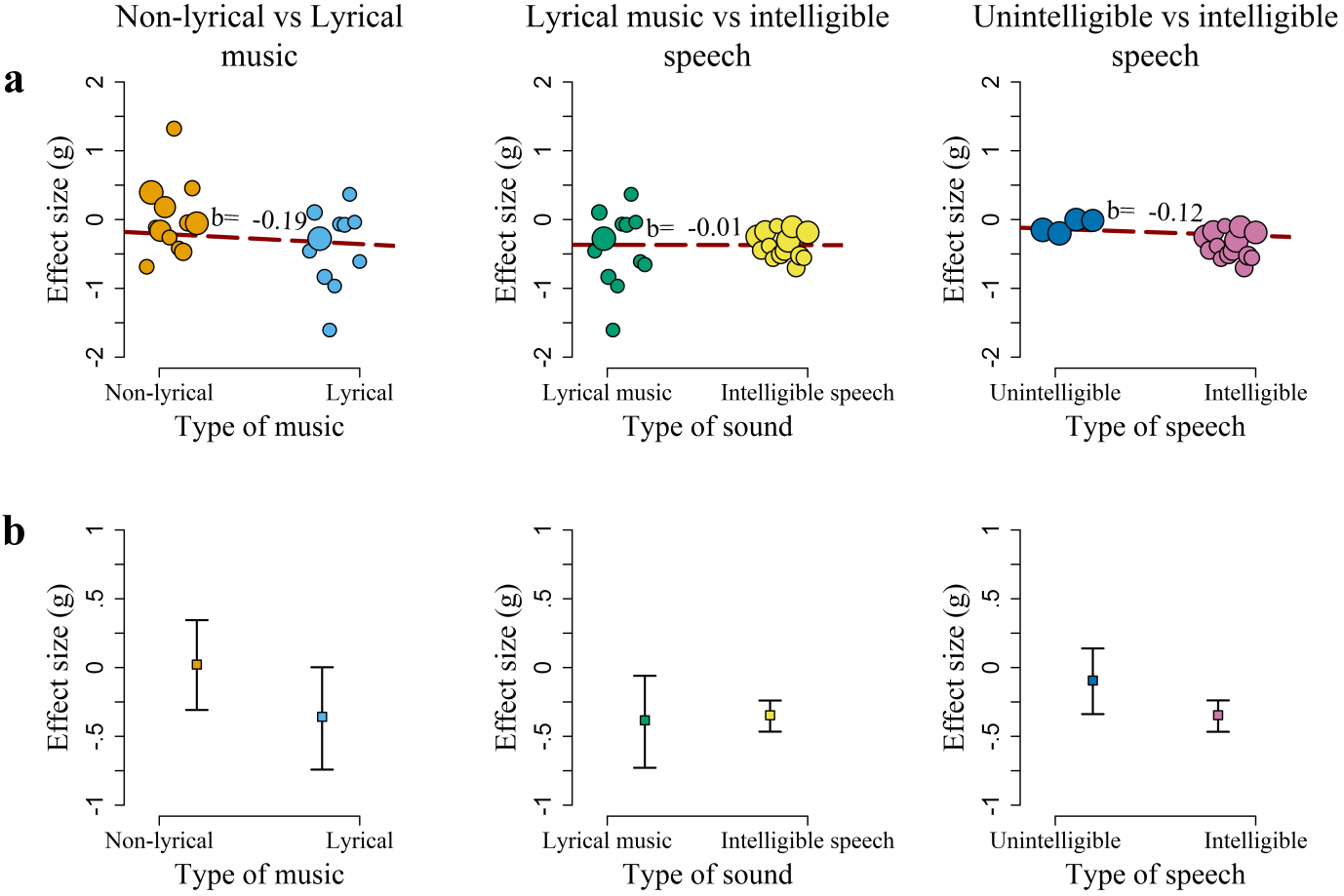
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*Figure 4*. Forest plot for the main effect of background music (**a**), speech (**b**), and noise (**c**) on reading comprehension. Plotted are the observed (i.e. empirical) effect sizes with their 95% confidence intervals, and the posterior effect size estimate from the meta-analysis model and the corresponding 95% CrIs. The size of squares is proportional to the weight of each study (i.e., the inverse of the within-study 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).

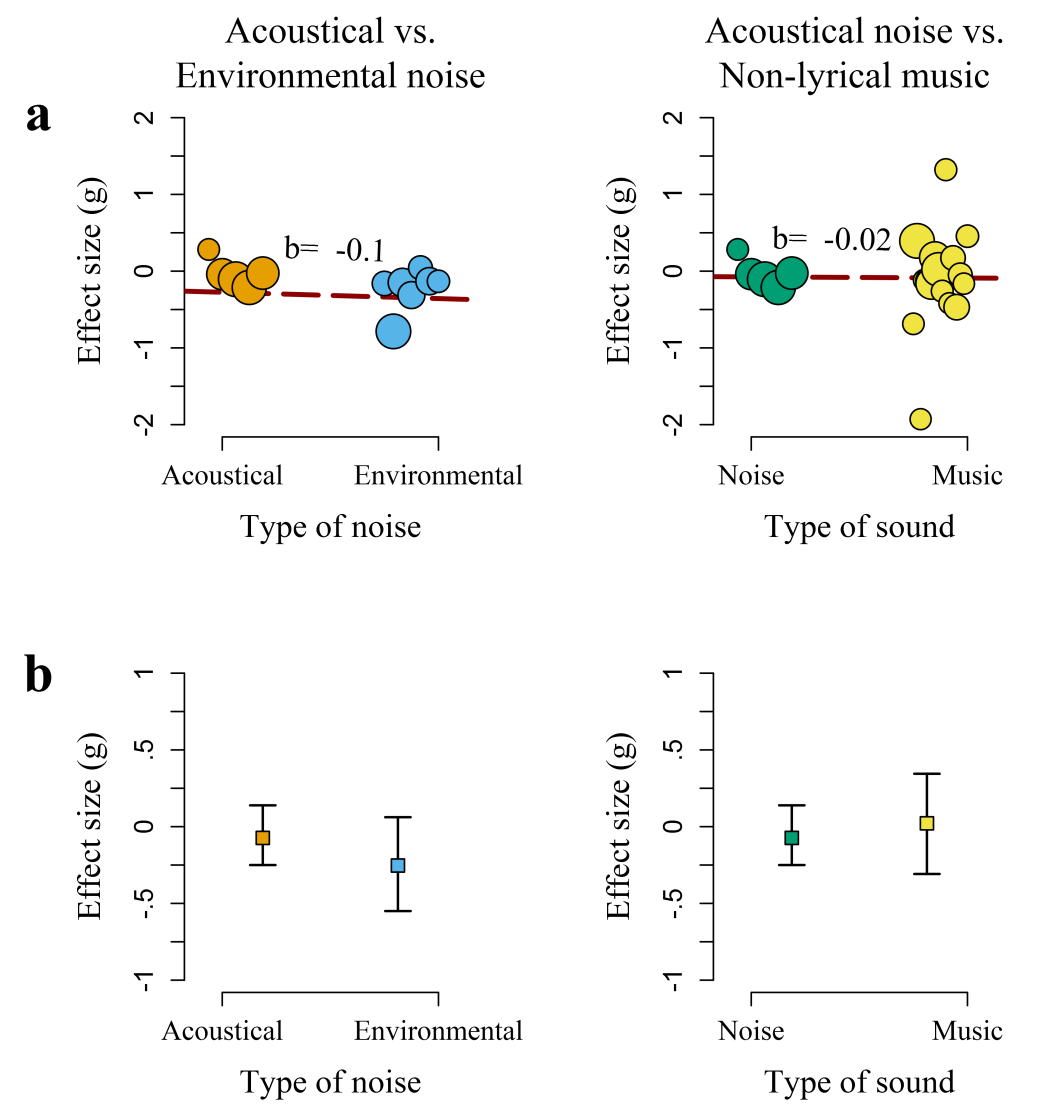
**Meta-regression**

The results from the meta-regression models testing the theoretical predictions outlined in the introduction are presented in Figures 5 and 6. Recall that the models yield a regression slope, which shows the estimated mean difference between the two groups, after adjusting for the precision of individual studies. Consistent with the semantic, but not with the phonological interference hypothesis, there was 99% probability that intelligible speech was more distracting than unintelligible speech (mean difference: g= -0.12). Additionally, in line with both the semantic and phonological interference hypotheses, there was 95% probability that lyrical music was more distracting than non-lyrical music (mean difference: g= -0.19). Surprisingly, however, intelligible speech and lyrical music did not differ between one another, and the estimated probability of a true difference was only 54% (with 50% being no difference, since the probability density mass would lie evenly to the left and right of 0).

Consistent with the changing-state hypothesis, there was 90% probability that environmental noise was more distracting than acoustical noise (mean difference: g= -0.10). However, there was only 55% probability of a difference between non-lyrical music and acoustical noise, thus suggesting that the two sound types did not generally differ. As Figure 6b shows, the size of both effects, as estimated by a random-effects meta-analysis, was very close to 0. This was result is contrary to the predicted difference from the changing-state hypothesis.

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*Figure 5*. Results of the meta-regression models testing the predictions of the semantic and phonological distraction hypotheses. Panel **a** shows the regression slope and the observed effect size of the studies included in the analysis. The slope indicates the mean difference estimated by the meta-regression model (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 within-study variance of the sampling distribution). Panel **b** shows the posterior effect size for each group, as estimated by a random-effects meta-analysis of the simple effect. Error bars show the 95% credible intervals.



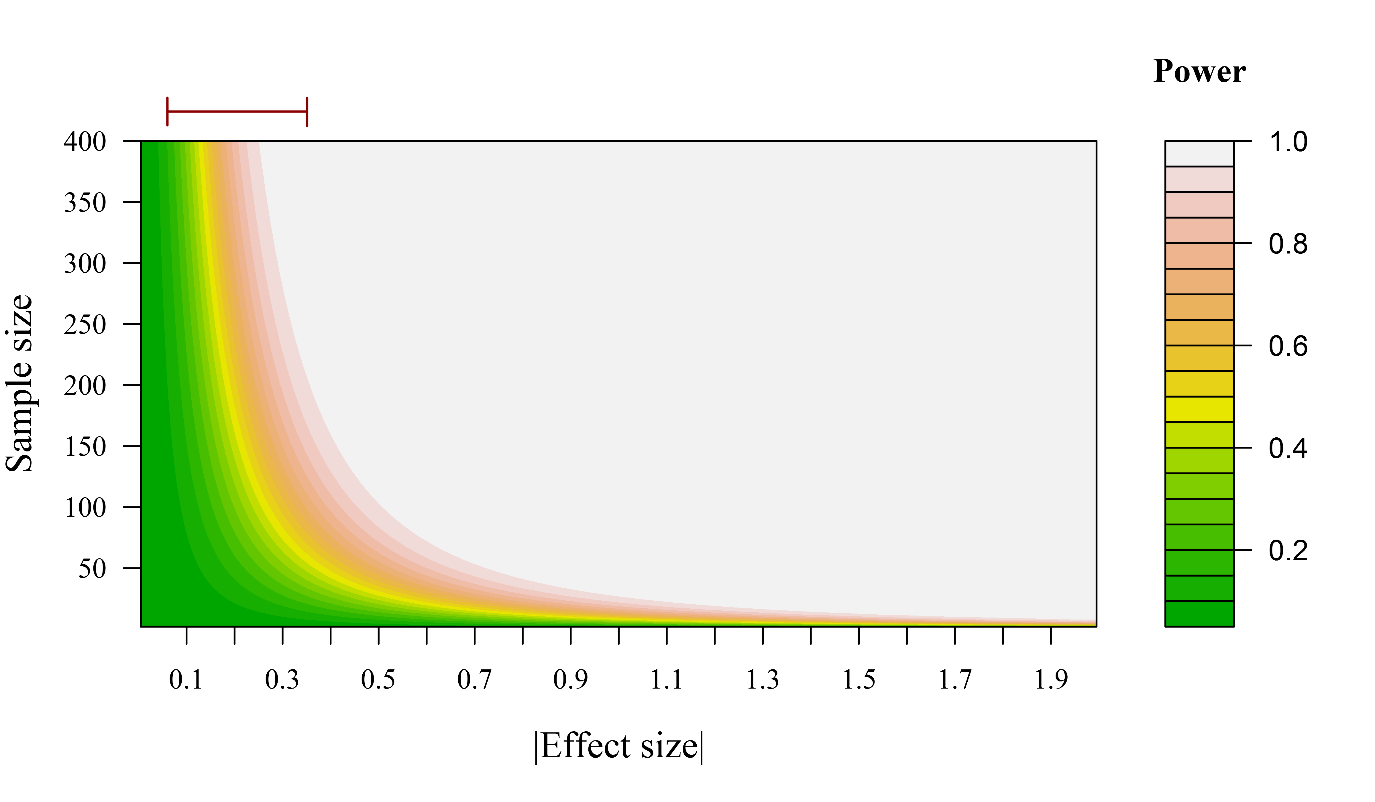
*Figure 6*. Results of the meta-regression models testing the predictions of the changing-state hypothesis. Panel **a** shows the regression slope and the observed effect size of the studies included in the analysis. The slope indicates the mean difference estimated by the meta-regression model (in terms of Hedges’s g) between the two groups. The size of circles is proportional to the weight of individual studies (inverse of the within-study variance of the sampling distribution). Panel **b** shows the posterior effect size for each group, as estimated by a random-effects meta-analysis of the simple effect. Error bars show the 95% credible intervals.

**Discussion**

The present study investigated the magnitude of auditory distraction effects during reading and how compatible these effects are with existing theories of auditory distraction. We will first consider the overall size of the effects and then discuss their theoretical implications. The main findings from the meta-analysis can be summarized as follows. First, background speech, noise, and music all had a negative effect (indicating distraction) on reading comprehension accuracy. The magnitude of the effects was small, but highly reliable, meaning that there was very high probability that these sounds are detrimental to reading comprehension given the available evidence. Second, auditory distraction effects measured with reading comprehension did not generally differ between adults and children. Finally, background speech, noise, and music had a very small, negative effect on reading speed, and background speech and noise also had a small, negative effect on proofreading accuracy. Although both effects proved to be smaller than the ones observed in reading comprehension, there was still high probability that they were negative (>90%).

Much of the interest in auditory distraction effects during reading is due to its practical implications for reading outside the psychological laboratory, yet the inconclusive evidence has made it difficult to derive clear conclusions until now. The present results advance our understanding of this topic by showing that external auditory input almost always comes at a cost for reading efficiently. Even though this cost is fairly modest, especially for measures such as reading speed and proofreading accuracy, there was still relatively high probability that it exists. Therefore, the present study resolves some of the controversy highlighted in the introduction by showing that general auditory distraction effects by background noise, speech, and music almost certainly exist, but that they are small in size.

Given that there was very high probability that background speech, noise, and music are detrimental to reading comprehension, why have some of the previous findings been so inconsistent? One likely reason is that some of the original studies may not have had sufficient power to detect the underlying effects. Figure 7 shows the relationship between sample size and statistical power for a range of effect sizes, including the ones observed in the present meta-analysis (cf. Wallisch, 2015). This is for illustrative purposes only, as statistical power is influenced not only by sample size and the magnitude of the true effect, but also by other factors, such as the reliability of the measure, missing data, sampling control and so on (Hansen & Collins, 1994). Nevertheless, as Figure 7 clearly shows, statistical power is related to sample size and generally a larger number of participants are required to achieve sufficient power of detecting some of the auditory distraction effects observed in the present study. This suggests that, although most of the observed effects are negative in sign, statistical significance may not always be achieved if the underlying effect is small and the experiment is underpowered.



*Figure 7*. An illustration of the sample sizes needed to achieve different levels of statistical power for a range of realistic effect sizes. Dark red interval at the top shows the range of effect sizes observed in the present meta-analysis. Desirable levels of statistical power are depicted by warm colors. Statistical power was calculated with the “pwr” R package (Champely, 2012) and is based on an independent-samples t-test with equal groups, and an α level of 0.05 (two-tailed).

The second goal of the present study was to

The theoretical side is also important as not all studies have explicitly explored the theoretical underpinnings of their work, with some researchers taking a more applied approach of investigating whether some type of sound is distracting to reading.

Interference-by-process vs interference-by-content: Martin et al.’s view seems very similar and almost indistinguishable from Marsh et al.’s. Quote discussion section of experiment 5 (penultimate sentence).

Arguably, the only meaningful distinction between

Phonological interference hypothesis- too restrictive since only speech gains access to attention? Also not supported by speech analysis.

Why are the effects so inconsistent? Although high prob of being negative, ESs are quite small. R

**Limitations**

Note that meta-regression results are observational in nature (Thompson & Higgins, 2002). Nevertheless, they are the first attempt to answer these questions by taking into account all the available evidence and we anticipate that the will prove to be very useful in guiding future experimental research.

Some of the meta-regression analyses were based on a smaller number of studies in one of the groups. However, this is not necessarily a limitation in the Bayesian approach that we have adopted here, because the results reflect our best understanding of auditory distraction effects given the currently available data. Once more data is available, the present results can be easily updated via Bayes’ theorem, which will make it possible to arrive at an even more precise estimate of the effects.

**Conclusion**

Auditory distraction during reading has been a topic of interest for the last 80 years, and as the surge of publications in the last few years shows, it is likely to be an active area of research for years to come.

As the number of studies in recent years shows, interest in this topic has not waned over the last several decades, and with the wider availability of eye-tracking methods, is likely to grow even more in the years to come.

**Acknowledgments**

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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 done in silence.

**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 | -0.24 | 0.01 |
| 1 | Sörqvist et al. 2010 | 40 | | adults | within | RS | speech | native | 72.5 | -0.05 | 0.01 |
| 2 | Ljung et al. 2009 | 70 | 50 | children | between | RC | noise | traffic | 62 | -0.16 | 0.03 |
| 2 | Ljung et al. 2009 | 70 | 50 | children | between | RS | noise | traffic | 62 | 0.71 | 0.04 |
| 2 | Ljung et al. 2009 | 70 | 66 | children | between | RC | speech | babble | 62 | 0.17 | 0.03 |
| 2 | Ljung et al. 2009 | 70 | 66 | children | between | RS | speech | babble | 62 | 0.21 | 0.03 |
| 3 | Fogelson 1973 | 14 | 14 | children | between | RC | music | pop | - | -0.42 | 0.14 |
| 4 | Tucker & Bushm. 1991 | 75 | 76 | adults | between | RC | music | rock & roll | 80 | 0.00 | 0.03 |
| 5 | Daoussis & McK. 1986 | 24 | 24 | adults | between | RC | music | rock | 50 | -0.52 | 0.08 |
| 6 | Etaugh & Michals 1975 | 32 | | adults | within | RC | music | preferred | - | -0.08 | 0.02 |
| 7 | Etaugh & Ptasnik 1982 | 20 | 20 | adults | between | RC | music | preferred | - | -0.74 | 0.10 |
| 8 | Kiger 1989 | 18 | 18 | children | between | RC | music | low load | - | 3.50 | 0.28 |
| 8 | Kiger 1989 | 18 | 18 | children | between | RC | music | high load | - | -0.69 | 0.11 |
| 9 | Miller & Schyb 1989 | 49 | 49 | adults | between | RC | music | classical | 47.5 | 0.11 | 0.04 |
| 9 | Miller & Schyb 1989 | 49 | 49 | adults | between | RC | music | pop | 47.5 | 0.23 | 0.04 |
| 9 | Miller & Schyb 1989 | 49 | 49 | adults | between | RC | music | vocal | 47.5 | -0.46 | 0.04 |
| 10 | Doyle & Furnham 2012 | 56 | | adults | within | RC | music | vocal | - | 0.10 | 0.01 |
| 11 | Anderson & Fuller 2010 | 334 | | children | within | RC | music | lyrical | 75 | -0.28 | 0.00 |
| 12 | Furnham & Strbac 2002 | 76 | | children | within | RC | noise | office | - | -0.78 | 0.01 |
| 12 | Furnham & Strbac 2002 | 76 | | children | within | RC | music | vocal/unfam. | - | -0.83 | 0.01 |
| 13 | Mullikin & Henk 1985 | 45 | | children | within | RC | music | classical | - | 0.39 | 0.01 |
| 13 | Mullikin & Henk 1985 | 45 | | children | within | RC | music | rock | - | -0.33 | 0.01 |
| 14 | Avila et al. 2011 | 19 | 20 | children | between | RC | music | vocal/ familiar | - | -1.61 | 0.13 |
| 14 | Avila et al. 2011 | 19 | 19 | children | between | RC | music | Instr./ familiar | - | -1.93 | 0.15 |
| 15 | Freeburne & Fleis. 1952 | 43 | 46 | adults | between | RC | music | classical | - | 0.02 | 0.04 |
| 15 | Freeburne & Fleis. 1952 | 43 | 46 | adults | between | RS | music | classical | - | -0.35 | 0.04 |
| 15 | Freeburne & Fleis. 1952 | 43 | 42 | adults | between | RC | music | pop | - | 0.04 | 0.05 |
| 15 | Freeburne & Fleis. 1952 | 43 | 42 | adults | between | RS | music | pop | - | -0.40 | 0.05 |
| 15 | Freeburne & Fleis. 1952 | 43 | 40 | adults | between | RC | music | semi-classical | - | -0.08 | 0.05 |
| 15 | Freeburne & Fleis. 1952 | 43 | 40 | adults | between | RS | music | semi-classical | - | -0.36 | 0.05 |
| 15 | Freeburne & Fleis. 1952 | 43 | 37 | adults | between | RC | music | jazz | - | -0.17 | 0.05 |
| 15 | Freeburne & Fleis. 1952 | 43 | 37 | adults | between | RS | music | jazz | - | -0.61 | 0.05 |
| 16 | Fendrick 1937 | 61 | 62 | adults | between | RC | music | semi-classical | - | -0.47 | 0.03 |
| 17 | Henderson et al. 1945 | 19 | 17 | adults | between | RC | music | classical | - | -0.12 | 0.11 |
| 17 | Henderson et al. 1945 | 19 | 14 | adults | between | RC | music | pop | - | -1.07 | 0.14 |
| 18 | Miller 2014 | 13 | 13 | adults | between | RC | music | classical lyrical | - | -0.84 | 0.16 |
| 18 | Miller 2014 | 13 | 17 | adults | between | RC | music | classical instr. | - | 0.13 | 0.13 |
| 18 | Miller 2014 | 13 | 11 | adults | between | RC | music | rock lyrical | - | -0.38 | 0.16 |
| 18 | Miller 2014 | 13 | 18 | adults | between | RC | music | rock instr. | - | -0.45 | 0.13 |
| 19 | Furnham & Allass 1999 | 16 | 16 | adults | between | RC | music | complex | - | -0.02 | 0.12 |

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 | - | -0.05 | 0.12 |
| 20 | Furnham & Bradl. 1997 | 10 | 10 | adults | between | RC | music | pop | - | -0.97 | 0.21 |
| 21 | Furnham at al. 1999 | 43 | 49 | children | between | RC | music | instrumental | - | -0.12 | 0.04 |
| 21 | Furnham at al. 1999 | 43 | 47 | children | between | RC | music | vocal | - | -0.07 | 0.04 |
| 22 | Perham & Currie 2014 | 30 | | adults | within | RC | music | disliked lyrical | 70 | -0.71 | 0.02 |
| 22 | Perham & Currie 2014 | 30 | | adults | within | RC | music | non-lyrical | 70 | -0.16 | 0.02 |
| 22 | Perham & Currie 2014 | 30 | | adults | within | RC | music | liked lyrical | 70 | -0.60 | 0.02 |
| 23 | Kelly 1994 | 13 | 12 | adults | between | RC | music | pop | 65 | -0.74 | 0.16 |
| 24 | Dove 2009 | 28 | 28 | adults | between | RC | music | sedat. classical | 62.5 | 0.10 | 0.07 |
| 24 | Dove 2009 | 28 | 28 | adults | between | RC | music | stimul. classical | 62.5 | 0.81 | 0.08 |
| 24 | Dove 2009 | 28 | 28 | adults | between | RS | music | sedat. classical | 62.5 | -0.07 | 0.07 |
| 24 | Dove 2009 | 28 | 28 | adults | between | RS | music | stimul. classical | 62.5 | -0.51 | 0.07 |
| 25 | Furnham et al. 1994 | 20 | | adults | within | RC | speech | TV drama | - | -0.45 | 0.03 |
| 26 | Johansson 1983 | 22 | 22 | children | between | RC | noise | continuous | 51 | 0.28 | 0.09 |
| 26 | Johansson 1983 | 22 | 22 | children | between | RC | noise | intermittent | 67.4 | 0.21 | 0.09 |
| 27 | Halin 2016 | 28 | | adults | within | RC | speech | native (easy) | 60 | -0.89 | 0.03 |
| 27 | Halin 2016 | 28 | | adults | within | RC | speech | native (diff) | 60 | -0.16 | 0.02 |
| 27 | Halin 2016 | 28 | | adults | within | RC | noise | traffic (easy) | 60 | -0.35 | 0.02 |
| 27 | Halin 2016 | 28 | | adults | within | RC | noise | traffic (diff) | 60 | -0.01 | 0.02 |
| 27 | Halin 2016 | 28 | | adults | within | RC | noise | aircraft (easy) | 60 | -0.23 | 0.02 |
| 27 | Halin 2016 | 28 | | adults | within | RC | noise | aircraft (diff) | 60 | -0.01 | 0.02 |
| 28 | Smith-J. & Klein 2009 | 54 | | adults | within | PR | speech | native | 65 | -0.04 | 0.01 |
| 29 | Cauchard et al. 2012 | 30 | | adults | within | RC | music | instrumental | 65 | 0.18 | 0.02 |
| 29 | Cauchard et al. 2012 | 30 | | adults | within | RC | speech | native | 65 | -0.17 | 0.02 |
| 29 | Cauchard et al. 2012 | 30 | | adults | within | RS | music | instrumental | 65 | 0.01 | 0.02 |
| 29 | Cauchard et al. 2012 | 30 | | adults | within | RS | speech | native | 65 | -0.20 | 0.02 |
| 30 | Johansson et al. 2012 | 24 | | adults | within | RC | music | preferred | 65 | -0.34 | 0.02 |
| 30 | Johansson et al. 2012 | 24 | | adults | within | RC | music | non-preferred | 65 | -0.67 | 0.03 |
| 30 | Johansson et al. 2012 | 24 | | adults | within | RC | noise | cafe | 65 | -0.31 | 0.02 |
| 30 | Johansson et al. 2012 | 24 | | adults | within | RS | music | preferred | 65 | -0.14 | 0.02 |
| 30 | Johansson et al. 2012 | 24 | | adults | within | RS | music | non-preferred | 65 | -0.10 | 0.02 |
| 30 | Johansson et al. 2012 | 24 | | adults | within | RS | noise | cafe | 65 | -0.07 | 0.02 |
| 31 | Weinstein 1974 | 15 | 18 | adults | between | PR† | noise | teletype | 70 | -0.56 | 0.12 |
| 31 | Weinstein 1974 | 15 | 18 | adults | between | PR‡ | noise | teletype | 70 | -1.26 | 0.14 |
| 32 | Weinstein 1977 | 29 | | adults | within | PR† | speech | native | 68 | -0.03 | 0.02 |
| 32 | Weinstein 1977 | 29 | | adults | within | PR‡ | speech | native | 68 | -0.29 | 0.02 |
| 33 | Martin et al. 1988, E1 | 36 | | adults | within | RC | speech | native | 82 | -0.20 | 0.01 |
| 33 | Martin et al. 1988, E1 | 36 | | adults | within | RC | speech | random | 82 | -0.18 | 0.01 |
| 33 | Martin et al. 1988, E1 | 36 | | adults | within | RC | music | instrumental | 82 | 0.00 | 0.01 |
| 33 | Martin et al. 1988, E1 | 36 | | adults | within | RC | music | random tones | 82 | -0.11 | 0.01 |
| 33 | Martin et al. 1988, E1 | 36 | | adults | within | RC | noise | white | 82 | -0.04 | 0.01 |
| 34 | Martin et al. 1988, E2 | 36 | | adults | within | RC | music | instrumental | 82 | 0.02 | 0.01 |
| 34 | Martin et al. 1988, E2 | 36 | | adults | within | RC | music | lyrical | 82 | -0.08 | 0.01 |
| 35 | Martin et al. 1988, E4 | 48 | | adults | within | RC | noise | white | 82 | -0.11 | 0.01 |

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, E4 | 48 | | adults | within | RC | speech | native | 82 | -0.31 | 0.01 |
| 35 | Martin et al. 1988, E4 | 48 | | adults | within | RC | speech | foreign | 82 | -0.15 | 0.01 |
| 36 | Martin et al. 1988, E5 | 48 | | adults | within | RC | noise | white | 82 | -0.21 | 0.01 |
| 36 | Martin et al. 1988, E5 | 48 | | adults | within | RC | speech | non-word | 82 | -0.20 | 0.01 |
| 36 | Martin et al. 1988, E5 | 48 | | adults | within | RC | speech | random words | 82 | -0.33 | 0.01 |
| 37 | Cool et al. 1994, E2 | 9 | | children | within | RS | music | radio/ generic | - | 0.13 | 0.05 |
| 37 | Cool et al. 1994, E2 | 9 | | children | within | RS | speech | movies | - | 0.20 | 0.05 |
| 37 | Cool et al. 1994, E2 | 9 | | children | within | RC | music | radio/ generic | - | -0.12 | 0.05 |
| 37 | Cool et al. 1994, E2 | 9 | | children | within | RC | speech | movies | - | -0.22 | 0.05 |
| 38 | Mitchell 1949 | 91 | | children | within | RTS | music | radio/ generic | - | -0.01 | 0.01 |
| 39 | Armstrong et al. 1991 | 33 | 30 | adults | between | RTS | speech | TV ads | - | -0.63 | 0.07 |
| 39 | Armstrong et al. 1991 | 33 | 32 | adults | between | RTS | speech | TV drama | - | -0.48 | 0.06 |
| 40 | Pool et al. 2000, E1 | 30 | 30 | children | between | RC | speech | TV soap opera | 60 | -0.38 | 0.07 |
| 40 | Pool et al. 2000, E1 | 30 | 30 | children | between | RC | music | TV music | 60 | -0.21 | 0.07 |
| 41 | Pool et al. 2000, E2 | 48 | 24 | children | between | RC | speech | TV soap opera | 60 | -0.57 | 0.06 |
| 41 | Pool et al. 2000, E2 | 48 | 24 | children | between | RC | music | TV music | 60 | -0.10 | 0.06 |
| 42 | Dockrell & Shield 2006 | 52 | 52 | children | between | RTS | noise | babble | 65 | -0.49 | 0.04 |
| 42 | Dockrell & Shield 2006 | 52 | 52 | children | between | RTS | noise | babble+environ. | 65 | 0.58 | 0.04 |
| 43 | Hyönä & Ekh. 2016, E1 | 42 | | adults | within | RC | speech | native | 82.5 | -0.17 | 0.01 |
| 43 | Hyönä & Ekh. 2016, E1 | 42 | | adults | within | RC | speech | foreign | 82.5 | 0.00 | 0.01 |
| 43 | Hyönä & Ekh. 2016, E1 | 42 | | adults | within | RS | speech | native | 82.5 | -0.02 | 0.01 |
| 43 | Hyönä & Ekh. 2016, E1 | 42 | | adults | within | RS | speech | foreign | 82.5 | 0.06 | 0.01 |
| 44 | Hyönä & Ekh. 2016, E2 | 36 | | adults | within | RS | speech | scrambl.-differ. | 82.5 | -0.15 | 0.01 |
| 44 | Hyönä & Ekh. 2016, E2 | 36 | | adults | within | RS | speech | scrambl.-same | 82.5 | -0.18 | 0.01 |
| 45 | Hyönä & Ekh. 2016, E3 | 35 | | adults | within | RS | speech | native | 82.5 | -0.13 | 0.01 |
| 45 | Hyönä & Ekh. 2016, E3 | 35 | | adults | within | RS | speech | scrambled | 82.5 | -0.20 | 0.01 |
| 46 | Hyönä & Ekh. 2016, E4 | 36 | | adults | within | RS | speech | scrambled-sem. | 82.5 | -0.11 | 0.01 |
| 46 | Hyönä & Ekh. 2016, E4 | 36 | | adults | within | RS | speech | scrm-syn+sem | 82.5 | -0.14 | 0.01 |
| 47 | Armstrong & Chng 2000 | 19 | 20 | adults | between | RC | speech | native | - | -0.09 | 0.10 |
| 48 | Madsen 1987, E1 | 50 | 50 | adults | between | RC | music | various | 75 | -0.10 | 0.04 |
| 49 | Sörqvist 2010, E1a | 23 | | children | within | RC | noise | aircraft | 57.5 | -0.13 | 0.02 |
| 50 | Sörqvist 2010, E1b | 23 | | children | within | RC | speech | native | 57.5 | -0.51 | 0.03 |
| 51 | Sörqvist et al. 2010, E1 | 24 | | adults | within | RC | speech | native | 65 | -0.46 | 0.02 |
| 52 | Sörqvist et al. 2010, E2 | 42 | | adults | within | RC | speech | native | 65 | -0.30 | 0.01 |
| 53 | Halin et al. 2014 | 32 | | adults | within | RC | speech | native | 65 | -0.10 | 0.02 |
| 54 | Halin et al. 2014, E1 | 31 | | adults | within | PR‡ | speech | native | 65 | -0.09 | 0.02 |
| 54 | Halin et al. 2014, E1 | 31 | | adults | within | PR† | speech | native | 65 | 0.20 | 0.02 |
| 55 | Halin et al. 2014, E2 | 29 | | adults | within | PR‡ | speech | native | 65 | -0.13 | 0.02 |
| 55 | Halin et al. 2014, E2 | 29 | | adults | within | PR† | speech | native | 65 | 0.11 | 0.02 |
| 56 | Haapakangas et al. 2011 | 54 | | adults | within | PR‡ | speech | native | 48 | -0.09 | 0.01 |
| 56 | Haapakangas et al. 2011 | 54 | | adults | within | PR† | speech | native | 48 | -0.11 | 0.01 |
| 57 | Baker & Madell 1965 | 24 | | adults | within | RC | speech | native | - | -0.70 | 0.03 |
| 58 | Vasilev et al. n.d. | 40 | | adults | within | RC | noise | speech-spectr. | 60 | -0.03 | 0.01 |
| 58 | Vasilev et al. n.d. | 40 | | adults | within | RC | speech | foreign | 60 | -0.01 | 0.01 |

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 |
| 58 | Vasilev et al. n.d. | 40 | | adults | within | RC | speech | native | 60 | -0.07 | 0.01 |
| 58 | Vasilev et al. n.d. | 40 | | adults | within | RS | noise | speech-spectr. | 60 | 0.04 | 0.01 |
| 58 | Vasilev et al. n.d. | 40 | | adults | within | RS | speech | foreign | 60 | -0.06 | 0.01 |
| 58 | Vasilev et al. n.d. | 40 | | adults | within | RS | speech | native | 60 | -0.15 | 0.01 |
| 59 | Falcon 2017, Sample 1 | 22 | 20 | children | between | RC | music | classical | 55 | -0.26 | 0.09 |
| 60 | Falcon 2017, Sample 2 | 25 | 28 | children | between | RC | music | classical | 55 | 1.32 | 0.09 |
| 61 | Ahuja 2016 | 20 | | adults | within | RC | music | liked | 60 | -0.71 | 0.04 |
| 61 | Ahuja 2016 | 20 | | adults | within | RC | music | disliked | 60 | -0.08 | 0.02 |
| 62 | Kou et al. 2017 | 31 | 29 | adults | between | RC | music | pop (vocal) | 65 | 0.37 | 0.07 |
| 62 | Kou et al. 2017 | 31 | 32 | adults | between | RC | noise | office | 65 | -0.13 | 0.06 |
| 63 | Sukowski et al. 2016 | 12 | | adults | within | RC | speech | native | 59.5 | -0.62 | 0.05 |
| 64 | Yan et al. 2017 | 42 | | adults | within | RS | speech | native | 62 | -0.16 | 0.01 |
| 64 | Yan et al. 2017 | 42 | | adults | within | RS | speech | meaningless | 62 | 0.06 | 0.01 |
| 65 | Gillis 2016 | 24 | 47 | adults | between | RC | music | various | - | 0.07 | 0.06 |

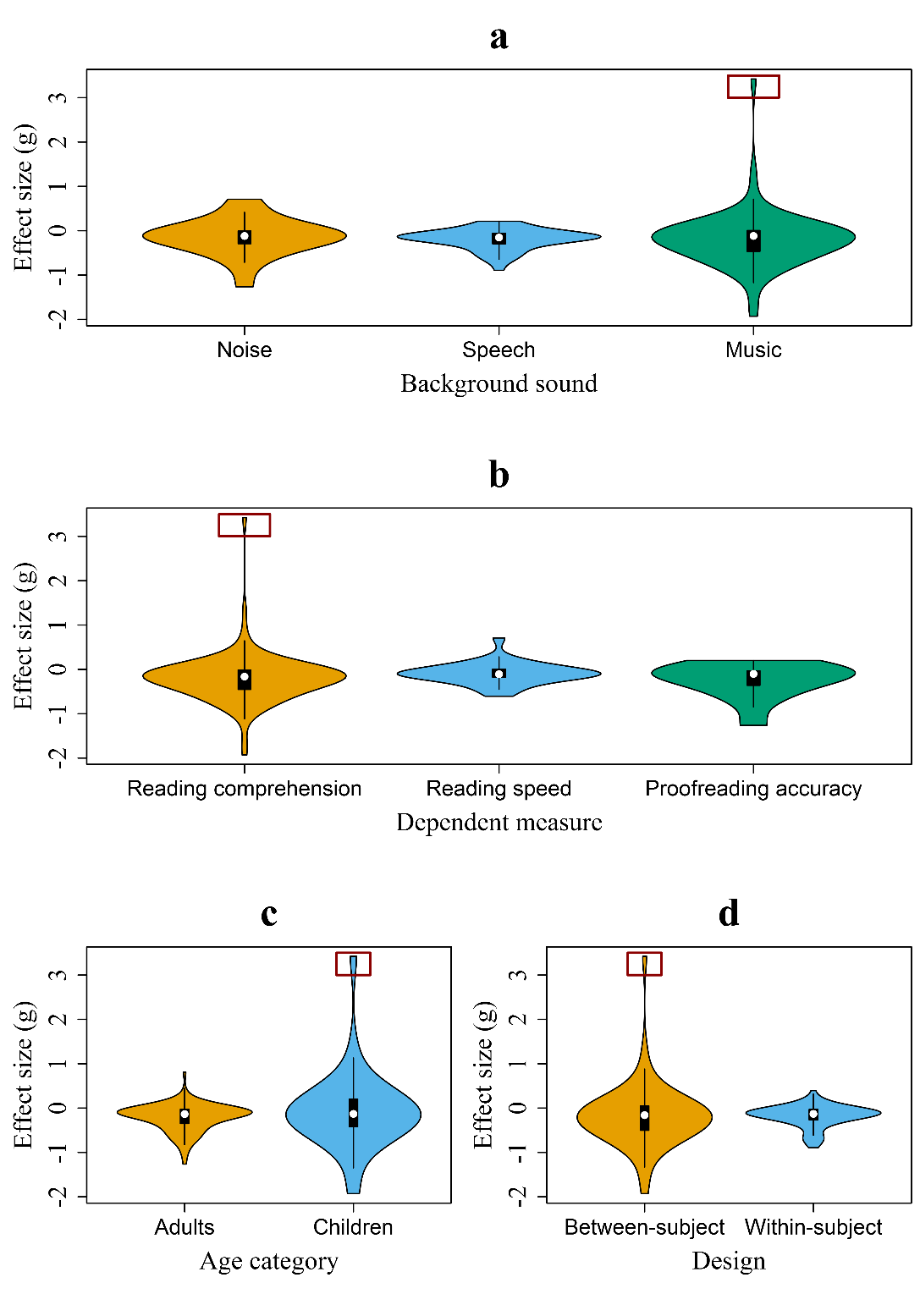
*Note*: NC: number of participants in the control (silence) condition. NE: number of participants in the experimental (sound) condition. RC: Reading comprehension. RS: reading speed. RTS: Reading test score. PR: Proofreading accuracy. ES: Effect size in Hedges’ g.

† Non-contextual errors (proofreading accuracy)

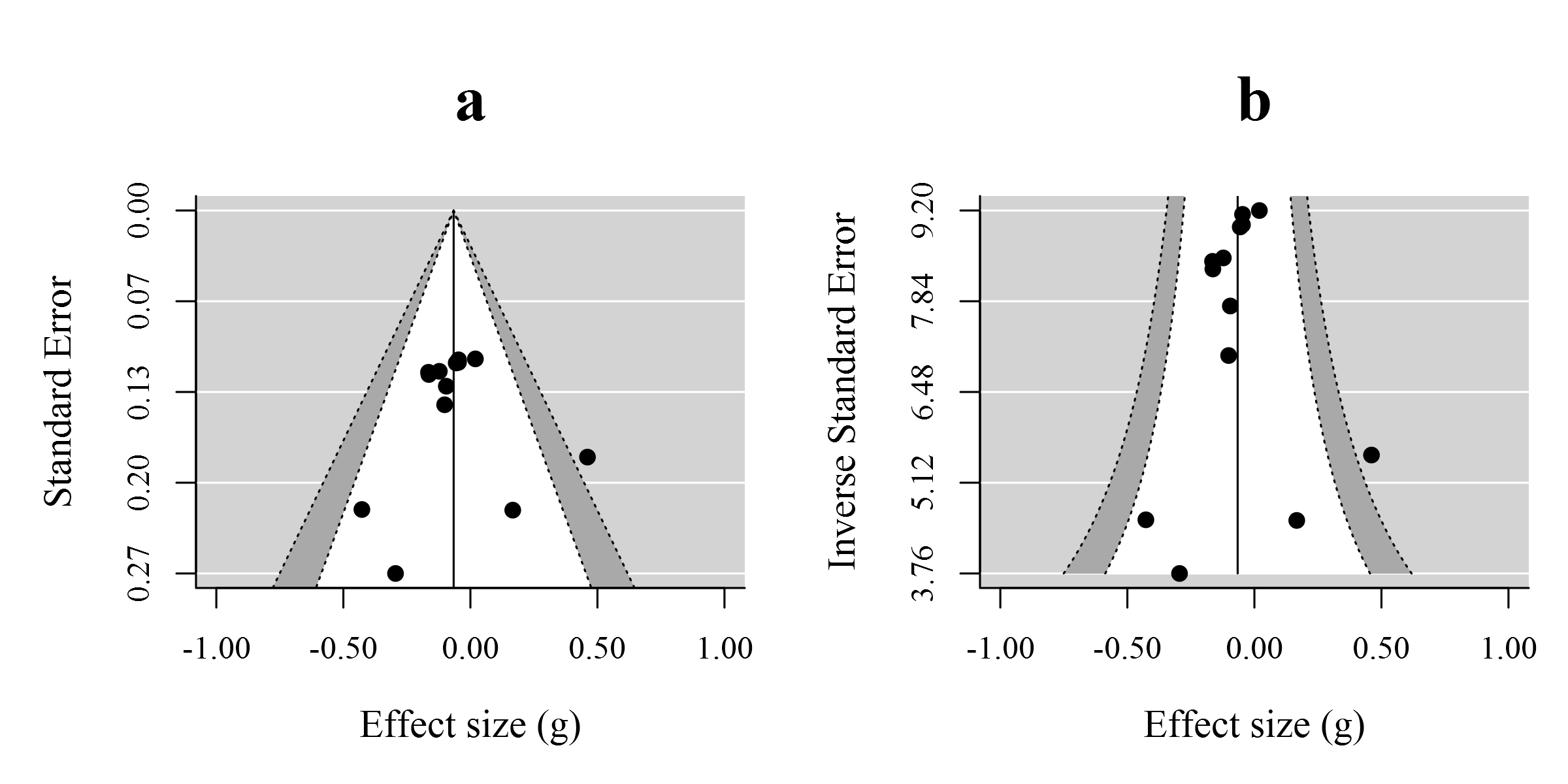
‡Contextual errors (proofreading accuracy)

Supplemental Material

**Visualization of Effect Sizes**

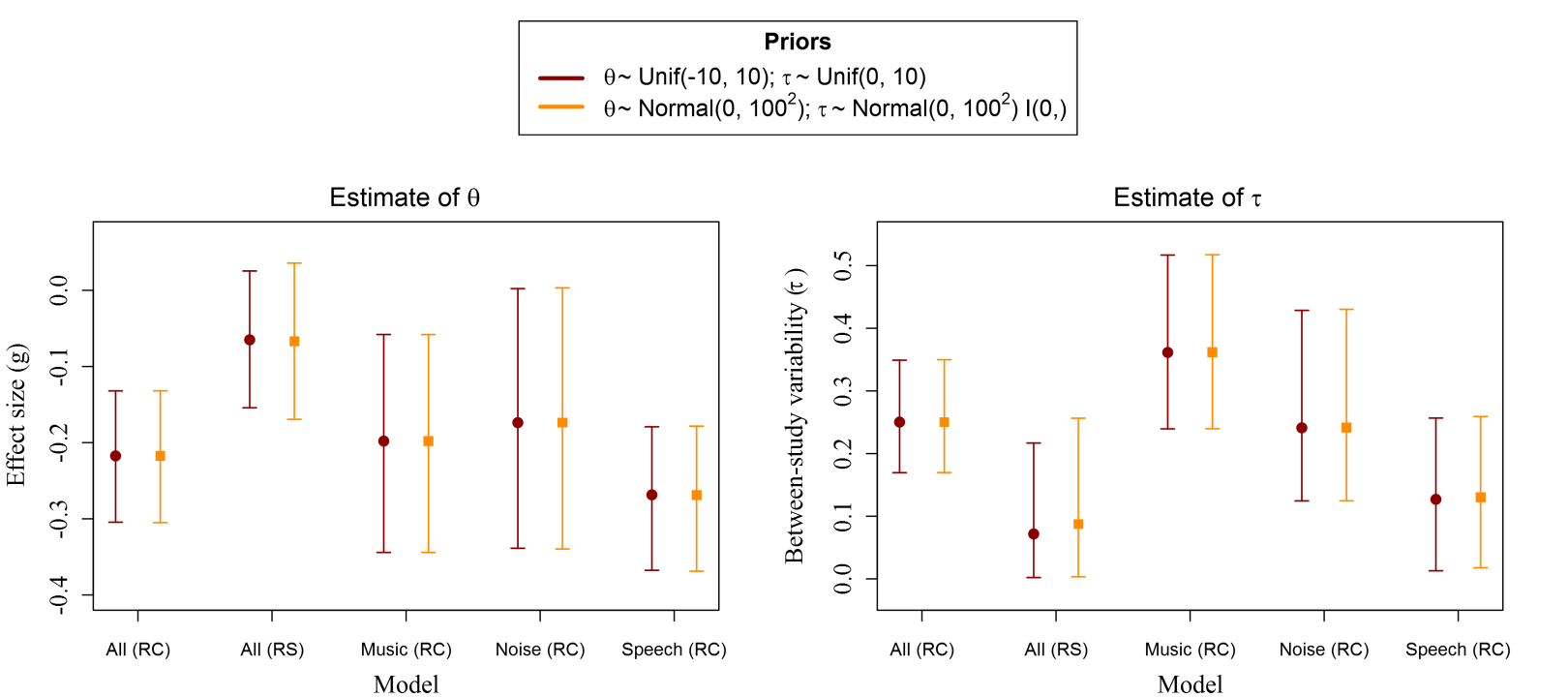
****

*Figure S1*. 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**; computed after transforming within-subject effect sizes with Morris & DeShon’s, 2002, formula 11). Red rectangle shows one effect size that was excluded as an outlier.

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*Figure S2*. Funnel plot of reading speed effect sizes plotted against their standard error (**a**) and the inverse of their standard error.

**Prior Sensitivity Analysis**



*Figure S3*. 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 (orange) did not change the main results reported in the paper. All: all studies. RC: reading comprehension. RS: reading speed.

**Robustness Check (Leave-one-out Method)**

Robustness analyses were carried out by using the leave-one-out method (see Greenhouse, & Iyengar, 2009) to ensure that individual studies did not have very large influence on the effect size estimate. In this method, the meta-analysis is repeated by omitting one different study each time. The summary statistics of the results are reported in Table S1. Overall, the effect sizes changed little by omitting each one of the studies. The effect size range for proofreading accuracy was slightly bigger, but this was likely due to the small number of studies in this analysis (7). This greater variability is not unusual for random-effects meta-analysis with few studies because there is more uncertainty in estimating the between-study variance in the model (cf. Welton et al., 2012).

Table S1

*Summary of the Robustness Analysis Using the Leave-one-out Method*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Analysis | ES reported in main paper | Leave-one-out | | | |
| Mean ES | SD of ES | Min ES | Max ES |
| Reading comprehension |  | | | | |
| All sounds | -0.21 | -0.21 | 0.006 | -0.23 | -0.19 |
| Noise | -0.17 | -0.17 | 0.02 | -0.19 | -0.11 |
| Speech | -0.26 | -0.26 | 0.01 | -0.28 | -0.24 |
| Music | -0.19 | -0.19 | 0.01 | -0.22 | -0.16 |
| Reading speed | -0.06 | -0.06 | 0.01 | -0.09 | -0.05 |
| Proofreading accuracy | -0.14 | -0.15 | 0.04 | -0.19 | -0.08 |

**Lyrical vs Non-lyrical meta-regression:**

Alternative coding. g= -18 vs g=- 12; p(b<0|D)=0.95 vs 0.83. Alternative coding results in slightly smaller mean difference and greater uncertainty. However, even so the conclusions from the paper remain unchanged. Consider plotting the two distributions.

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1. Four studies did not contain any information that made it possible to calculate the effect sizes. As all of the studies were more than 25 years old, it was not possible to obtain the data from the authors. Therefore, these studies were discarded (they did not count towards the number of included studies). [↑](#footnote-ref-1)
2. Add about exception here (lyrical vs non-lyrical music). [↑](#footnote-ref-2)