

Auditory Distraction During Reading: A Bayesian Meta-Analysis of a Continuing Controversy

Perspectives on Psychological Science
1–31

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DOI: 10.1177/1745691617747398

www.psychologicalscience.org/PPS



Martin R. Vasilev , **Julie A. Kirkby**, and **Bernhard Angele**

Department of Psychology, Bournemouth University

Abstract

Everyday reading occurs in different settings, such as on the train to work, in a busy cafeteria, or at home while listening to music. In these situations, readers are exposed to external auditory stimulation from nearby noise, speech, or music that may distract them from their task and reduce their comprehension. Although many studies have investigated auditory-distraction effects during reading, the results have proved to be inconsistent and sometimes even contradictory. In addition, the broader theoretical implications of the findings have not always been explicitly considered. We report a Bayesian meta-analysis of 65 studies on auditory-distraction effects during reading and use metaregression models to test predictions derived from existing theories. The results showed that background noise, speech, and music all have a small but reliably detrimental effect on reading performance. The degree of disruption in reading comprehension did not generally differ between adults and children. Intelligible speech and lyrical music resulted in the biggest distraction. Although this last result is consistent with theories of semantic distraction, there was also reliable distraction by noise. It is argued that new theoretical models are needed that can account for distraction by both background speech and noise.

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 the widespread use of personal radios among students in the 1940s (Henderson, Crews, & Barlow, 1945; L. R. 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 8 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 for 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 accumulated over the past several decades. In addition, because of the mixed findings on some topics, the actual magnitude of auditory-distraction effects—or even if they are reliably different from zero—is currently not well understood.

Corresponding Author:

Martin R. Vasilev, Department of Psychology, Bournemouth University, P104, Poole House, Talbot Campus, Fern Barrow, Poole, Dorset, BH12 5BB, United Kingdom
E-mail: mvasilev@bournemouth.ac.uk

In the present article, 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 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 metaregression 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 article 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

Background noise can be defined as any unwanted sounds that are not related to the reading task. Strictly speaking, some degree of background noise is always present during reading; however, the intensity of the background noise can vary enormously depending on the environment. A number of epidemiological studies have investigated the relationship between constant exposure to noise and reading and have suggested that long-term exposure to traffic noise is associated with lower reading ability in children (e.g., Haines, Stansfeld, Job, Berglund, & Head, 2001b; Hygge, Evans, & Bullinger, 2002; Papanikolaou, Skenteris, & Piperakis, 2015; Stansfeld et al., 2005). Note, however, that only very few studies have examined the effect of short-term experimental exposure to noise.

In one early study, C. R. Johansson (1983) found that the reading comprehension and reading speed of 10-year-old children did not differ between quiet conditions and conditions of continuous or intermittent acoustical noise. More recently, Dockrell and Shield (2006) investigated the effect of typical classroom noise (which is quite different from acoustical white or pink noise) on reading comprehension in 8-year-old children. Participants completed the Suffolk Reading Scale in one of three conditions: silence, noise consisting of children's babble, and the same babble combined with intermittent environmental noise. The results showed that children performed better in the quiet condition 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, Sorqvist, and Hygge (2009) found that road-traffic noise impaired the reading speed of 12- and 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 the materials were identical (e.g., Martin, Wogalter, & Forlano, 1988, Experiments 4 and 5). Although most studies have failed to find an effect of acoustical or environmental noise on reading comprehension (Gawron, 1984; Jahncke, Hygge, Halin, Green, & Dimberg, 2011; R. Johansson, Holmqvist, Mossberg, & Lindgren, 2012; Veitch, 1990), others have found such an effect after examining the mediating role of personality characteristics, such as introversion and extroversion (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

Background speech is a specific kind of noise that often occurs in daily life. Compared with environmental and acoustical noise, background speech has specific acoustic properties that make it salient to listeners. In addition, if the background speech is intelligible, it also carries semantic meaning (completely unintelligible background speech might also occur, but it is not very frequently encountered unless one is in a foreign country and does not understand the language). Perhaps owing to its semantic content, background speech is often rated as more distracting and more annoying than acoustical noise (Haapakangas et al., 2011; Haka et al., 2009; 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). In addition, some evidence suggests that this disruption effect may be larger for participants who have a poorer ability to immediately suppress the irrelevant background speech (Sörqvist, Halin, & Hygge, 2010; Sörqvist, Ljungberg, & Ljung, 2010).

A specific reading task that has been investigated in more detail in connection with background speech is proofreading. Proofreading is an important part of many professions, especially those related to teaching

and publishing. 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 investigated in proofreading studies: contextual mistakes, which require understanding the meaning of the text to detect (e.g., problems with pronoun agreement), and noncontextual mistakes, which require only processing of the current word to detect (e.g., spelling mistakes). Because of 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 noncontextual errors.

Some support for this prediction was found by an early study by Weinstein (1977), who reported that background speech consisting of a radio news report significantly impaired the detection of contextual errors but not the detection of noncontextual errors. However, Jones, Miles, and Page (1990) found exactly the opposite effect in another study. The authors manipulated both the intelligibility of background speech (which was played either normally or in reverse) 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 noncontextual 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 reduced the overall accuracy on a similar proofreading task compared with continuous noise. However, even though the task included both contextual and noncontextual 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 with broadband noise (i.e., noise consisting of a wide range of frequencies), did not affect proofreading performance for either contextual or noncontextual errors. The auditory stimuli were presented at a sound intensity level comparable to that used in 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.

It is noteworthy that 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, 2014; Halin, Marsh, Hellman, Hellström, & Sörqvist, 2014). In a few experiments, Halin and his colleagues showed that performance on

a reading/proofreading task was disrupted by background speech only when the text was formatted in a familiar font, but not when it was formatted in an unfamiliar font (i.e., one that was more difficult to read). Likewise, performance was disrupted only 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 (for a discussion, see Sörqvist & Marsh, 2015).

Most studies that have been considered so far have investigated only the end product of reading and proofreading (i.e., comprehension accuracy, proofreading 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 fixation probabilities (Cauchard, Cane, & Weger, 2012; Hyönä & Ekholm, 2016; Vasilev, Liversedge, Rowan, Kirkby, & Angele, 2017; Yan, Meng, Liu, He, & Paterson, 2017). One key finding from these studies is that background speech leads to an increased number of rereading fixations. Although these studies have been successful in explaining when disruption by background speech occurs during the reading process, one puzzling aspect is that none of the eye-tracking experiments have replicated the disruption effect in comprehension accuracy found in behavioral studies. Why this inconsistency exists remains unknown, but it raises questions about the reliability of the effect of background speech on reading comprehension.

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 of the semantic meaning of the speech sound. These effects appear to be more reliable than the effect of nonspeech noise on reading, which has not been consistently replicated. Nevertheless, several recent studies 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 done deliberately as 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 record players and their use by students. However, these early studies did not paint a clear picture of the relationship between background music and reading. Although some of them found that music can negatively affect reading comprehension in children and university students (Fendrick, 1937; Fogelson, 1973; Henderson et al., 1945), others found that background music either does not affect reading at all (Freeburne & Fleischer, 1952; L. R. Miller, 1947; Mitchell, 1949) or that it actually improves reading performance (Hall, 1952). Indeed, this controversy has persisted until the present day; even the only two eye-tracking studies to address this question (Cauchard et al., 2012; R. Johansson et al., 2012) have failed to find any effect of background music on fixation durations or fixation probabilities during reading.

To examine what conditions might give rise to distraction, some studies 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 & Stephenson, 2007; Furnham & Strbac, 2002; Furnham, Trew, & Sneade, 1999; Kou, McClelland, & Furnham, 2017). These studies have predicted, on the basis of Eysenck's (1967) theory of personality, that individuals high in extraversion will be distracted less by background music than individuals high in introversion because of the extroverts' higher cortical arousal threshold. However, the results from these studies have been mixed. Although some of them have found such an interaction between personality traits and background music (Daoussis & McKelvie, 1986; Furnham & Bradley, 1997; Furnham & Strbac, 2002), others have not (Avila et al., 2011; Furnham & Allass, 1999; Furnham & Stephenson, 2007; Furnham et al., 1999; Kou et al., 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; L. K. 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 rarely study while listening to music. In contrast, R. Johansson et al. (2012) found that participants had lower comprehension accuracy when listening to nonpreferred music compared with a quiet control condition, but there was no such

effect when they listened to preferred music. In addition, they did not replicate the previous finding that participants' studying habits modulated the results. Adding further to the confusion, Perham and Currie (2014) found that preferred and nonpreferred lyrical music (i.e., music with sung lyrics) 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 (W. F. Thompson, Schellenberg, & Letnic, 2012); its familiarity to participants (Hilliard & Tolin, 1979); and its capability to induce a startle response (Ravaja & Kallinen, 2004). These results are quite interesting in terms of understanding what types of music might 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.

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: Many studies report nonsignificant effects on reading comprehension. Although the effect of background speech on reading appears to be more reliable, several experiments have also failed to find an 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 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 in which memories are registered and rehearsed through a process of subvocalization. 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 acoustical noise. In addition, a distraction effect was observed even if the speech sound was in a language that participants

could not understand (Salamé & Baddeley, 1987). The authors argued that this occurs 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 the first to systematically test the phonological-interference 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 (which was intelligible to participants) was more distracting than Russian speech (which was unintelligible to participants). Likewise, a continuous speech stream of random words was found to disrupt comprehension more than a continuous speech stream of nonwords. 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 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 can then interfere with maintaining the serial order of items in a memory task.

Although reading is a more complex cognitive task than serial recall of items, it also involves maintaining the order of words in the sentence and their syntactic relations. For example, because models of parallel word processing such as SWIFT (Saccade generation With Inhibition by Foveal Targets; Engbert, Nuthmann, Richter, & Kliegl, 2005) assume that readers can process multiple words at the same time, they also have to assume, at least implicitly, that readers are somehow able to maintain information about the order of these

words in the current sentence. In addition, some models of reading comprehension (e.g., Kintsch, 1998) assume that word meanings are combined to form propositions or “idea units” according to their syntactic relationships (Kintsch & Rawson, 2005). Forming these units must also involve establishing and keeping track of the order of words in the sentence, as well as their syntactic relationships.

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, 2010b), according to which 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 “AAAAAABA” would capture attention because another “A” is expected in the sequence (Hughes, 2014; for a review of similar effects caused by deviant sounds, see Parmentier, 2014).

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. The difference between the two accounts is very subtle: According to Marsh et al. (2008, 2009), 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 the semantic properties of the speech cause the interference. These two very similar views are difficult to disentangle empirically, and because they make the same prediction for the purposes of the present analysis, we will consider them together. 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 showed that background noise, speech, and music may be detrimental to reading performance but that considerable uncertainty exists as

to the reliability and the magnitude of such distraction effects. This uncertainty makes it difficult to draw firm conclusions about the experimental effects and their real-world significance. Are background sounds reliably disruptive to reading, and is this disruption large enough to be of any practical significance? In addition, 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 enables us 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 (Jäger, Engelmann, & Vasishth, 2017; Marsman et al., 2017; Vasishth, 2015; Vasishth, Chen, Li, & Guo, 2013; see also Kruschke & Liddell, 2018). 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 preprocess words in parafoveal vision (Vasilev & Angele, 2017).

The two available (non-Bayesian) meta-analyses have addressed how background noise and music affect a wide range of behavioral and cognitive tasks (Kämpfe, Sedlmeier, & Renkewitz, 2010; Szalma & Hancock, 2011). Although 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. Kämpfe (2010) 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 eight 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 stimuli are detrimental to reading performance.

The second and more important goal of the present analysis was to investigate which 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 done, this does not tell us what makes these sounds distracting. As discussed previously, a few theories make specific predictions about what type of auditory stimuli should be distracting. Therefore, the second aim of the study was to test the predictions of these theories using Bayesian metaregression 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 study 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 summarized in Figure 1. The phonological-interference hypothesis (Salamé & Baddeley, 1982) makes the unique prediction that all types of speech sounds 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. In addition, the phonological-interference hypothesis is not capable of explaining distraction by nonspeech background noise and non-lyrical music because neither sound gains access to the phonological store.

The semantic-interference (Martin et al., 1988) and interference-by-process (Marsh et al., 2008) accounts both make the 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. In addition, they also predict that (a) lyrical music should be more distracting than nonlyrical music because the former contains lyrics that are intelligible to participants, and (b) intelligible speech should be more distracting than lyrical music because, on average, continuous speech has more semantic content than lyrical music.¹ However, because lyrical music that is intelligible to participants contains not only semantic information but also phonological information, it is not possible to rule out any involvement of phonology in this effect.

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 two further predictions. First, nonlyrical music should be more distracting than acoustical noise (e.g., white or pink noise) because the former exhibits

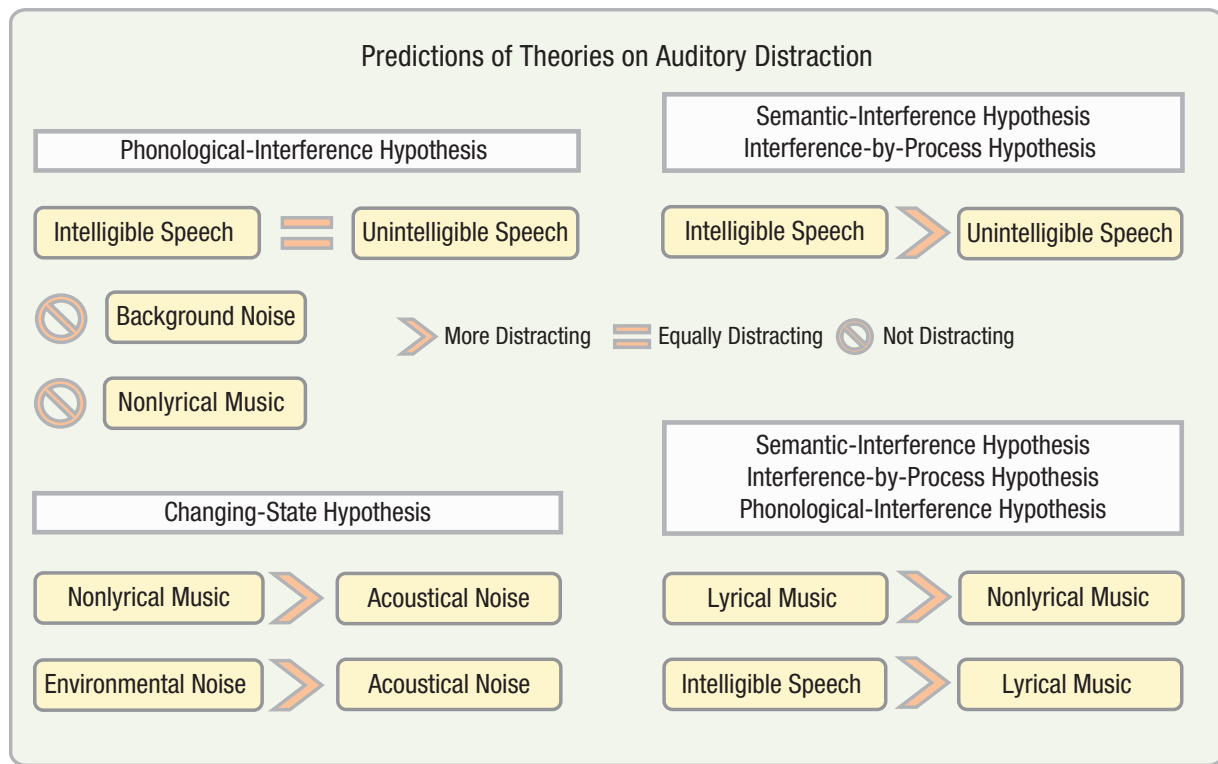


Fig. 1. A schematic summary of the predictions derived from theories on auditory distraction.

more acoustic variation than the latter. Nonlyrical 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) should again be more distracting than steady-state acoustical noise because it also exhibits more acoustic variation.

Method

The goal of a meta-analysis is to pool evidence from multiple studies to estimate some parameter of interest (e.g., the true difference in comprehension accuracy between reading in silence and reading with music in the background). A Bayesian meta-analysis differs from the classical (frequentist) meta-analysis in the sense that it uses Bayesian inference to estimate the parameter and the uncertainty surrounding this estimate. Before performing the analysis, the researcher needs to express his or her prior belief about the parameter in terms of a probability distribution. This is known as the *prior probability distribution*, and it reflects the researcher's belief about the parameter before observing the data. After the data are collected, a *likelihood function* is constructed, which essentially conveys how probable

the data are for different values of the parameter (Lynch, 2007). The result of Bayesian inference is a *posterior probability distribution*, which is the researcher's updated belief about the parameter *given* the observed data.

The posterior probability distribution is derived from Bayes's theorem, which states that the posterior distribution is proportional to the product of the prior probability distribution and the likelihood (i.e., $\text{posterior} \propto \text{prior} \times \text{likelihood}$; for more details, see Lynch, 2007). In the meta-analysis, the observed means are the empirical effect sizes (i.e., the differences between conditions) reported in the original studies. In contrast, the posterior mean of the effect sizes is simply the mean of the posterior probability distribution that is derived from the Bayesian meta-analysis. Therefore, the posterior mean reflects our updated belief about the size of the effect (i.e., the difference) in light of the observed data.

One important part of any meta-analysis is to assess the data for publication bias and other reporting biases. One common way to do this is to use what is known as a *funnel plot* (Egger, Smith, Schneider, & Minder, 1997; Sterne et al., 2011). This is a scatter plot of all the effect sizes included in the meta-analysis against some measure of their precision, such as the standard error or the inverse of the standard error. More precise studies (i.e., the ones with smaller standard errors) will

appear more narrowly at the top of the plot, whereas less precise studies (i.e., the ones with larger standard errors) will scatter more widely at the bottom. When there is no bias or heterogeneity between studies, the scatter of the plot will resemble a symmetrical inverted funnel (Sterne et al., 2011). *Funnel plot asymmetry* can occur if studies are missing from one side of the plot, thus creating an asymmetrical funnel shape. For example, this can happen if publication bias or other reporting biases are preventing the dissemination of studies with negative findings (however, reporting biases are not the only possible source of asymmetry, and other factors need to be explored as well; see Sterne et al., 2011).

Literature search

The search of the literature was conducted by following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher, Liberati, Tetzlaff, Altman, & The 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,” and “background music AND reading.” Each search for one of the three background sounds was done separately. The literature search covered articles published before June 25, 2017. In addition, we examined 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).

When searching the literature, it is important to consider relevant studies that have been conducted but never published in a peer-reviewed journal or an edited book (i.e., the so-called file-drawer problem; Rosenthal, 1979). This issue was addressed through some of the databases that were searched. ProQuest Dissertations contains more than 2 million doctoral and masters’ dissertations (Lefebvre, Manheimer, & Glanville, 2008), which often contain unpublished research. In addition, Google Scholar indexes a wide range of unpublished sources, such as conference proceedings, dissertations, reports, and preprints. Furthermore, author searches were carried out for researchers who have done work on this topic in the past 2 decades. These searches included researcher networking web sites, such as ResearchGate.net and Academia.edu, that also contain unpublished research (e.g., conference presentations or unpublished manuscripts). In the present meta-analysis, unpublished studies accounted for 17% of all

screened records, thus showing that the search strategy was effective in locating them (unpublished studies typically make up 8%–10% of all sources in systematic reviews and meta-analyses; Clarke & Clarke, 2000; Lefebvre et al., 2008). These unpublished studies came from different sources, such as dissertations, conference proceedings, reports, and unpublished manuscripts.

The identified articles were evaluated against the inclusion criteria presented in Appendix A. In short, the studies had to (a) experimentally manipulate background noise, speech, or music in a reading or a proof-reading task; (b) have a sound methodological design; and (c) include reading in silence as a baseline condition. The inclusion criteria were developed before the meta-analysis with the help of a smaller, qualitative review of the literature. Epidemiological studies of extended 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, of the experiments for which eligibility was assessed, 44% were included in the meta-analysis. Although the inclusion rate may appear to be low, it was necessary to ensure that only studies that were similar enough to be analyzed together were included. Information about the included studies and their effect sizes is presented in Appendix B.

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 are based on reading-comprehension accuracy. 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.

For the metaregression analyses, additional information about the type of sound manipulation was also extracted (e.g., whether the noise was environmental or acoustical, or whether the music was lyrical or nonlyrical). If a study contained a background-music manipulation, M. R. Vasilev listened to the songs to determine whether they were lyrical or nonlyrical. Only studies that could be unambiguously classified as either lyrical or nonlyrical were added to this metaregression analysis.

Effect-size calculation

Standardized effect sizes of the mean difference (g) and their variances were calculated from the reported

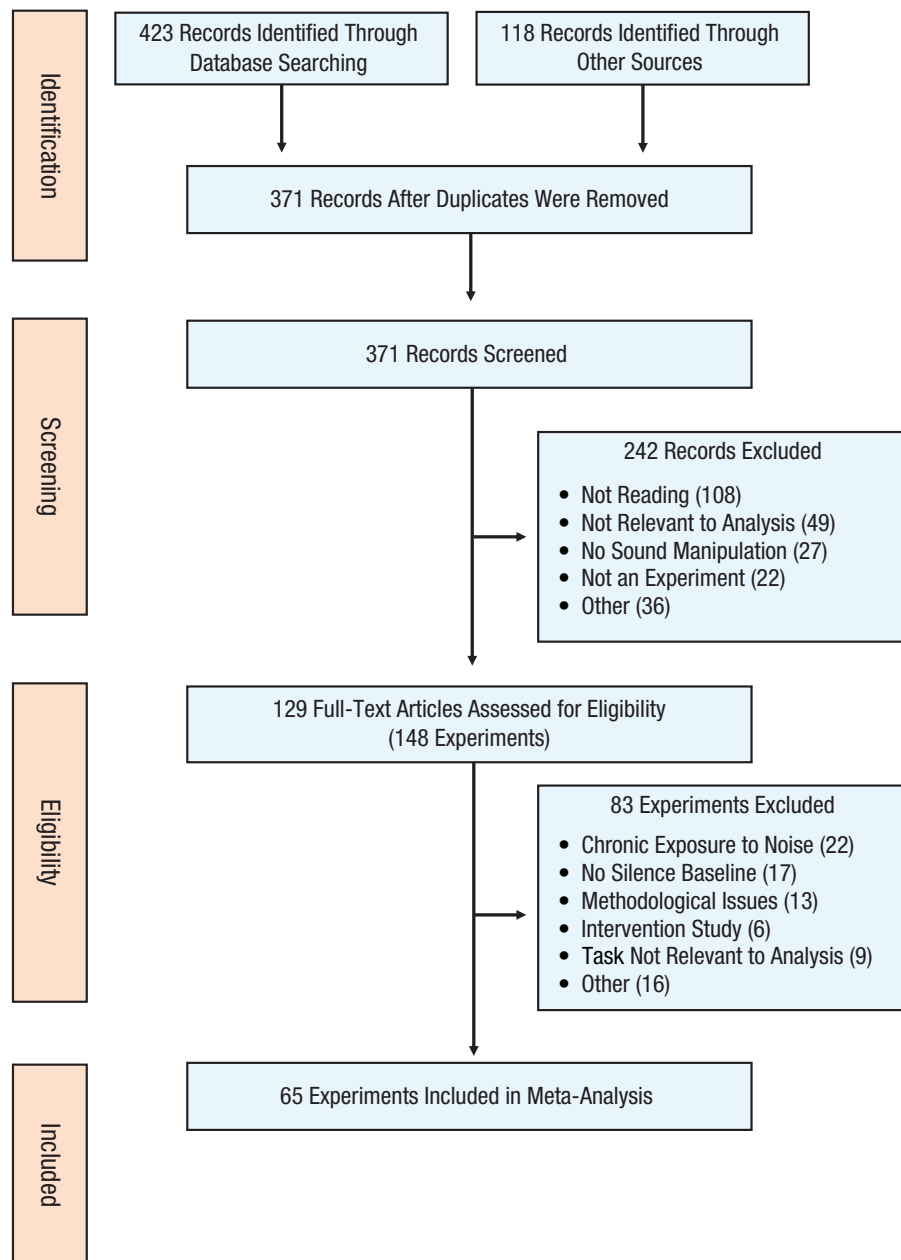


Fig. 2. A flowchart illustrating the stages of the literature-search process.

descriptive statistics. This was done by first calculating Cohen's d for the respective design of the study and then applying Hedges's g correction for small sample bias (Hedges & Olkin, 1985). The effect sizes were calculated with formulas 12.11 to 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 an experimental sound condition and reading in silence in a control condition. If descriptive statistics were unavailable or incomplete, the effect sizes were calculated by digitizing graphs (Rohatgi, 2015) or converted/approximated

from the reported test statistics using existing formulas (Borenstein, 2009; Lajeunesse, 2013).² In the analysis of reading-comprehension accuracy and proofreading accuracy, studies were coded so that negative effect sizes indicate lower comprehension/proofreading accuracy in an experiment's sound condition. Likewise, in the analysis of reading speed, negative effect sizes also indicate slower reading speed in the experimental sound condition compared with the silent control condition. One effect size was excluded as an outlier (see Fig. S1 in the Supplemental Material available online).

Because 55.5% of the studies used a within-subjects 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 one estimate from a study (L. R. Miller, 1947) that reported the required statistics. These represented a wide range of experimental sound types and included measures of both reading comprehension and reading speed. 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 to calculate the effect sizes for all studies that had a within-subjects design.

Effect sizes from within- and between-subjects 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-subjects studies were transformed to make them comparable with the effect sizes of between-subjects studies. This was done using Formula 11 from Morris and DeShon (2002). In addition, because some studies yielded more than one effect size, care was taken to avoid statistical nonindependence in the analyses (for a recent overview, see Noble, Lagisz, O'dea, & Nakagawa, 2017). 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).³

Publication bias

In the present meta-analysis, 12.3% of all included studies were from the so-called gray literature (i.e., they were not formally published in a peer-reviewed journal or in an edited book at the time of analysis). To assess the data for publication bias and other related biases, we performed a number of visual and statistical tests using the *meta* (Schwarzer, 2007) and *metafor* (Viechtbauer, 2010) packages for the R software environment (R Core Team, 2016). The visualization of the results for reading comprehension is presented in Figure 3 (for the reading-speed results, see the Supplemental Material). The funnel plots (Figs. 3a and 3b) indicate 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 performed on the basis of a weighted linear regression of the effect estimates on their standard errors (Sterne et al., 2011), which revealed no statistically significant evidence of asymmetry for either reading

comprehension, $t(52) = -0.42$, $p = .67$, or reading speed, $t(11) = 0.08$, $p = .93$. Proofreading accuracy was not considered here because funnel-plot tests of asymmetry are not recommended when there are fewer than 10 studies; (Sterne et al., 2011). In addition, metaregression analyses (Figs. 3e and 3f) 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.

Data analysis

Meta-analysis. The common choice in meta-analysis is between a fixed-effects model and a random-effects model. A fixed-effects 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, T_i , is assumed to come from a normal distribution with some mean θ and variance σ_i^2 :

$$T_i \sim \text{Normal}(\theta, \sigma_i^2) \quad i = 1, 2, 3, \dots, n. \quad (1)$$

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 true effect size between studies (Welton et al., 2012). In this case, T_i , the observed effect size of the i th study, is assumed to be generated by a unique underlying true effect for that i th study, denoted here as θ_i . This unique underlying effect θ_i is in turn assumed to come from a normal distribution with some (unknown) mean θ and a between-studies variance of τ^2 :

$$T_i \sim \text{Normal}(\theta_i, \sigma_i^2) \quad i = 1, 2, 3, \dots, n, \quad (2)$$

$$\theta_i \sim \text{Normal}(\theta, \tau^2).$$

Therefore, the true 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-studies heterogeneity was expected as a result of 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; Vasilev & Angele, 2017; Vasishth et al., 2013). The full Bayesian

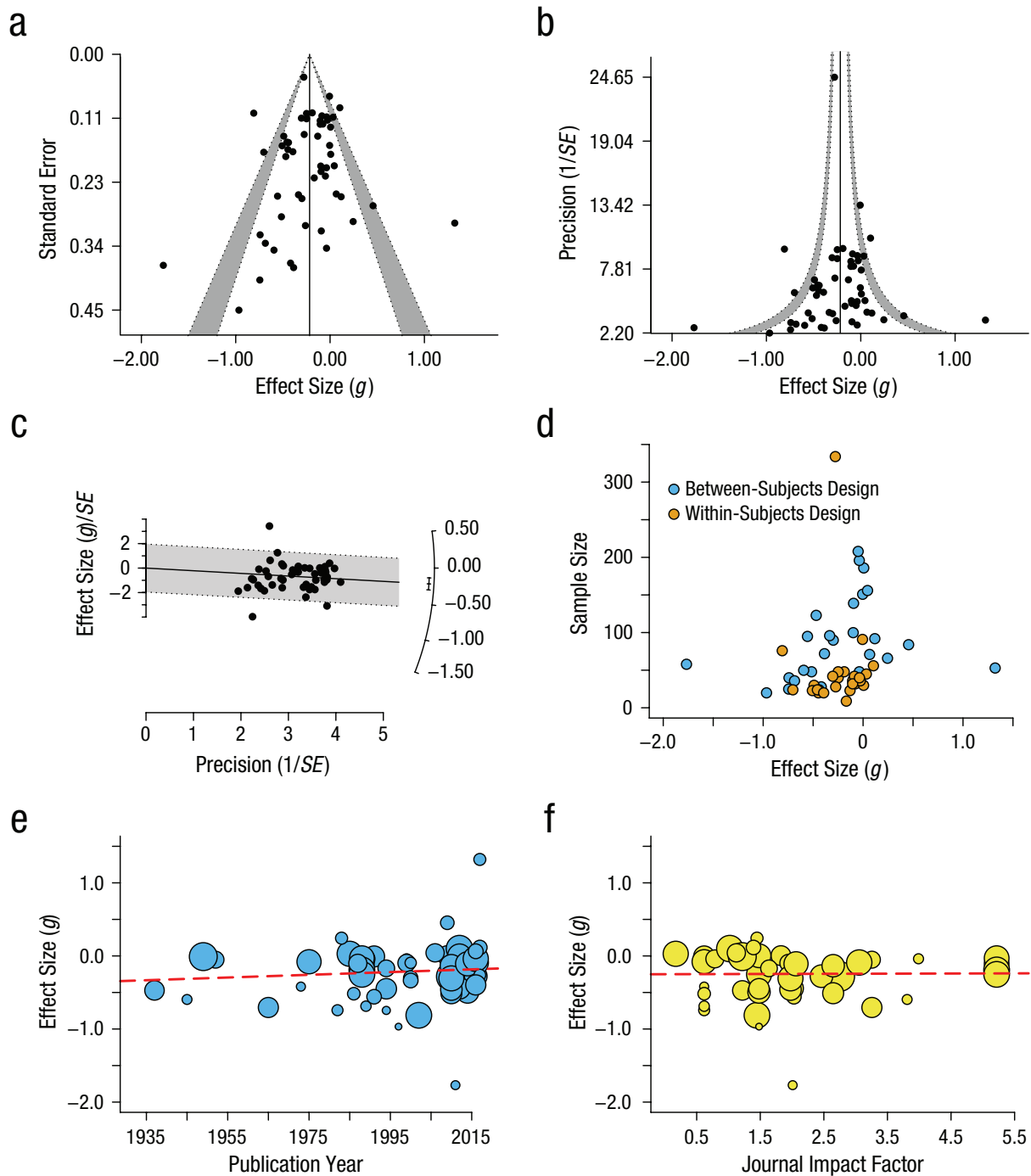


Fig. 3. Visual assessment of publication bias and other related biases in the literature on reading-comprehension accuracy (presentation format adapted from Nakagawa, Noble, Senior, & Lagisz, 2017, Fig. 6). The funnel plots show (a) standard error and (b) precision (i.e., the inverse of the standard error) as a function of effect size. The white area within the gray bounds shows the 95% pseudo-confidence interval; the gray bands extend this area to the 99% pseudo-confidence interval. (See the main text for information on how to interpret funnel plots.) The vertical lines indicate the pooled effect size, as estimated from a random-effects meta-analysis. The radial or Galbraith plot (c) shows the z statistic (i.e., the effect size divided by its standard error) of each study as a function of precision. The arc on the right side of the plot corresponds to the size of the individual observed effects. The interval next to the arc shows the pooled effect size and its 95% confidence interval. The gray area highlights the region in which z values between -2 and 2 lie and is the same as the approximate 95% confidence interval; on average, 95% of the studies are expected to fall within this range (Anzures-Cabrera & Higgins, 2010). The vertical scatter of effect sizes shows the degree of heterogeneity in the data. The scatterplot in (d) shows the relationship between effect sizes and sample sizes, broken down by study design type (i.e., between subjects vs. within subjects). The scatterplots (with best-fitting regression lines) in the bottom row show the results of metaregression models examining the relationship (e) between effect size and publication year and (f) between effect size and impact factor of the journal where the study was published.

model was defined as follows (Jäger et al., 2017; Schmid & Mengersen, 2013):

$$\begin{aligned} T_i | \theta_i, s_i^2 &\sim \text{Normal}(\theta_i, s_i^2) \quad i = 1, 2, 3, \dots, n \\ \theta_i | \theta, \tau^2 &\sim \text{Normal}(\theta, \tau^2) \\ \theta &\sim \text{Uniform}(-10, 10) \\ \tau &\sim \text{Uniform}(0, 10). \end{aligned} \quad (3)$$

T_i is the observed effect size (in Hedges's g) in the i th study; θ_i is the true auditory-distraction effect in the i th study; S_i^2 is the true sampling variance of the i th study, estimated from the within-studies variance of the sampling distribution of study i ; θ is the unknown true auditory-distraction effect estimated by the model; and τ^2 is the unknown between-studies variance. In this model, precision was defined as the inverse of the within-studies 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. Because these are vague priors, 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 $(0, 10^4)$ for θ and Normal $(0, 10^4)$ $I(0, \cdot)$ for τ (the normal distribution was truncated at 0). The sensitivity analysis indicated that the choice of priors did not influence the results (see the Supplemental Material).

Metaregression. 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 metaregression models to investigate how different study characteristics (e.g., whether the background music was lyrical or nonlyrical) are associated with the observed effect sizes. Metaregression 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-studies 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 boldface type indicates the added parameters; Jäger et al., 2017; Welton et al., 2012):

$$T_i | \theta_i, \beta, s_i^2 \sim \text{Normal}(\theta_i + \beta \mathbf{x}_i, s_i^2) \quad i = 1, 2, 3, \dots, n \quad (4)$$

$$\theta_i | \theta, \tau^2 \sim \text{Normal}(\theta, \tau^2)$$

$$\theta \sim \text{Uniform}(-10, 10)$$

$$\tau \sim \text{Uniform}(0, 10)$$

$$\beta \sim \text{Uniform}(-10, 10).$$

β is the regression coefficient for the underlying effect of the covariate x_i ; θ_i is the true auditory-distraction effect in the i th study, adjusted for the covariate effect x_i ; and θ is the unknown true auditory-distraction effect, also adjusted for the covariate effect x_i . All remaining parameters have the same interpretation as in Equation 3. The contrasts used for the covariate x_i are presented in Table 1. These contrasts were used to test the predictions outlined in the introduction.

Posterior sampling. The posterior probability distribution was sampled with JAGS (Plummer, 2003) using the R software environment (R Core Team, 2016). Five Markov-chain Monte Carlo (MCMC) chains were run with 100,000 iterations each. Checks were made to ensure that the starting values of the MCMC chains did not influence the results. The first 3,000 iterations were considered a burn-in period and were discarded. A thinning interval of 5 was used for the MCMC chains (i.e., every fifth sample was retained) to reduce the influence of autocorrelation. The summary of the posterior distribution was based on

Table 1. Type of Metaregression Comparisons and the Contrast Coding of Covariates

| Comparison | Covariate levels | | Contrast coding | |
|---|------------------|---------------|-----------------|---------|
| | Level 1 | Level 2 | Level 1 | Level 2 |
| Nonlyrical vs. lyrical music | Nonlyrical | 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 |

20,000 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 effective sample size (ESS) of the MCMC chains was calculated for every parameter and contrast of interest. The ESS is the size of the MCMC chain after adjusting it for autocorrelation (Kass, Carlin, Gelman, & Neal, 1998; Kruschke, 2015). All of the present analyses had an ESS greater than 10,000, as recommended by Kruschke (2015). This was necessary for achieving a stable estimation of the credible interval limits: This estimation depends on sparse regions of the posterior probability distribution that are sampled less often by the MCMC chain (Kruschke, 2015).

The results are presented as the estimate of the effect sizes of interest and their corresponding 95% credible intervals. Unlike 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 (see Morey, Hoekstra, Rouder, Lee, & Wagenmakers, 2016). All probabilities reported in the article 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 article. However, Nicenboim and Vasishth (2016) provide an accessible overview.

Results

Meta-analysis

The results from the meta-analysis are presented in Table 2. In addition, 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 (Hedges's $g = -0.21$), 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 (Hedges's $g = -0.26$) than either background noise (Hedges's $g = -0.17$) or background music (Hedges's $g = -0.19$). Nevertheless, the effect size for each of the three sound types was fairly small.

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 (note that this does not allow us to conclude that there is no true effect, only that it is possible that the true effect size is 0). 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 is a very high probability that background speech, noise, and music are detrimental to reading comprehension, reading speed, and proofreading accuracy.

Although it is possible to use Bayes factors to perform hypothesis testing (e.g., see Rouder & Morey, 2011; Rouder, Morey, & Province, 2013), the emphasis in the present meta-analysis was on estimating the magnitude of auditory-distraction effects. The findings from this meta-analysis suggest that nonnull effects almost certainly exist, even if their magnitude is small. Therefore, even if a Bayes factor were to favor a null hypothesis relative to some alternative hypothesis, the prior probability that the null hypothesis was exactly true would be negligible in this case. Because of this, the posterior probability of the null hypothesis would remain small.

Because our analyses included both studies with adults as participants and studies with children as participants, we carried out metaregression models to test whether the effect sizes differed between adults and children. Only reading comprehension was considered in these analyses because 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 with studies with adults, after adjusting for their precision in the analysis. Overall, the difference between adults and children was very close to 0; thus, 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 (Hedges's $g = 0.05$). In addition, the effect was not highly reliable because there was only a 73% probability of a true mean difference. Taken together, these results suggest that effect sizes for reading comprehension did not generally differ between adults and children. For this reason, child and adult studies were analyzed together in all remaining analyses.

Metaregression

The results from the metaregression models testing the theoretical predictions outlined in the introduction are presented in Figures 5 and 6. Recall that the models yield a regression slope that shows the estimated mean

Table 2. Posterior Effect Size Estimates of Auditory-Distraction Effects and 95% Credible Intervals From the Meta-Analysis

| Type of analysis | <i>n</i> | Mean ES (Hedges's <i>g</i>) | 95% CrI | $p(\text{ES} < 0 \mid \text{Data})$ | τ^2 | ESS |
|-----------------------|----------|---------------------------------|----------------|-------------------------------------|----------|-------|
| Reading comprehension | | | | | | |
| All sounds | 54 | -0.21 | [-0.30, -0.13] | > .99 | 0.06 | 91803 |
| Noise | 12 | -0.17 | [-0.33, 0.002] | .97 | 0.06 | 92499 |
| Speech | 20 | -0.26 | [-0.36, -0.17] | > .99 | 0.02 | 47662 |
| Music | 36 | -0.19 | [-0.34, -0.05] | > .99 | 0.13 | 93678 |
| Reading speed | | | | | | |
| All sounds | 13 | -0.06 | [-0.15, 0.02] | .92 | 0.01 | 20915 |
| Speech | 6 | -0.08 | [-0.20, 0.03] | .92 | 0.01 | 28612 |
| Proofreading accuracy | | | | | | |
| Speech and Noise | 7 | -0.14 | [-0.42, 0.04] | .94 | 0.04 | 40097 |
| Speech ^a | 6 | -0.09 | [-0.30, 0.07] | .90 | 0.02 | 41296 |

Note: *n* = number of studies in the analysis; ES = effect size; $p(\text{ES} < 0 \mid \text{Data})$ = probability that background sounds are detrimental to reading, given the data (i.e., probability that the effect size is smaller than 0); CrI = credible interval; τ^2 = estimated between-studies variance; ESS = effective sample size of the Markov-chain Monte Carlo chains for the main parameter of interest (θ).

^aIntelligible speech only.

difference between the two groups after adjusting for the precision of individual studies. Consistent with the semantic-interference hypothesis but not with the phonological-interference hypothesis, there was a 99% probability that intelligible speech was more distracting than unintelligible speech (mean difference: Hedges's $g = -0.12$). In addition, in line with both the semantic- and phonological-interference hypotheses, there was a 95% probability that lyrical music was more distracting than nonlyrical music (mean difference: Hedges's $g = -0.19$). Note, however, that there was no difference between intelligible speech and lyrical music, and the estimated probability of a true difference was only 54% (50% = no difference, because the posterior probability density would lie evenly to the left and right side of 0). This last result is surprising because, arguably, most people perceive lyrical music to be subjectively less distracting than intelligible speech. For example, it can be speculated that students may be more likely to choose to study while listening to lyrical music in the background than they are to study while listening to an audio book. However, the present results suggest that lyrical music and intelligible speech are equally distracting.

Consistent with the changing-state hypothesis, there was a 90% probability that environmental noise was more distracting than acoustical noise (mean difference: Hedges's $g = -0.10$). However, there was only a 55% probability of a difference between nonlyrical music and acoustical noise, which suggests that the two background 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 result is contrary to the predicted difference from the changing-state hypothesis.

Discussion

In the present study, we investigated the magnitude of auditory-distraction effects during reading and the compatibility of these effects with existing theories of distraction. We will first consider the overall size of the effects and then discuss their theoretical and practical 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 a 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 a high probability that they were negative (> 90%).

The present results provide the first comprehensive analysis of auditory-distraction effects in a reading task.

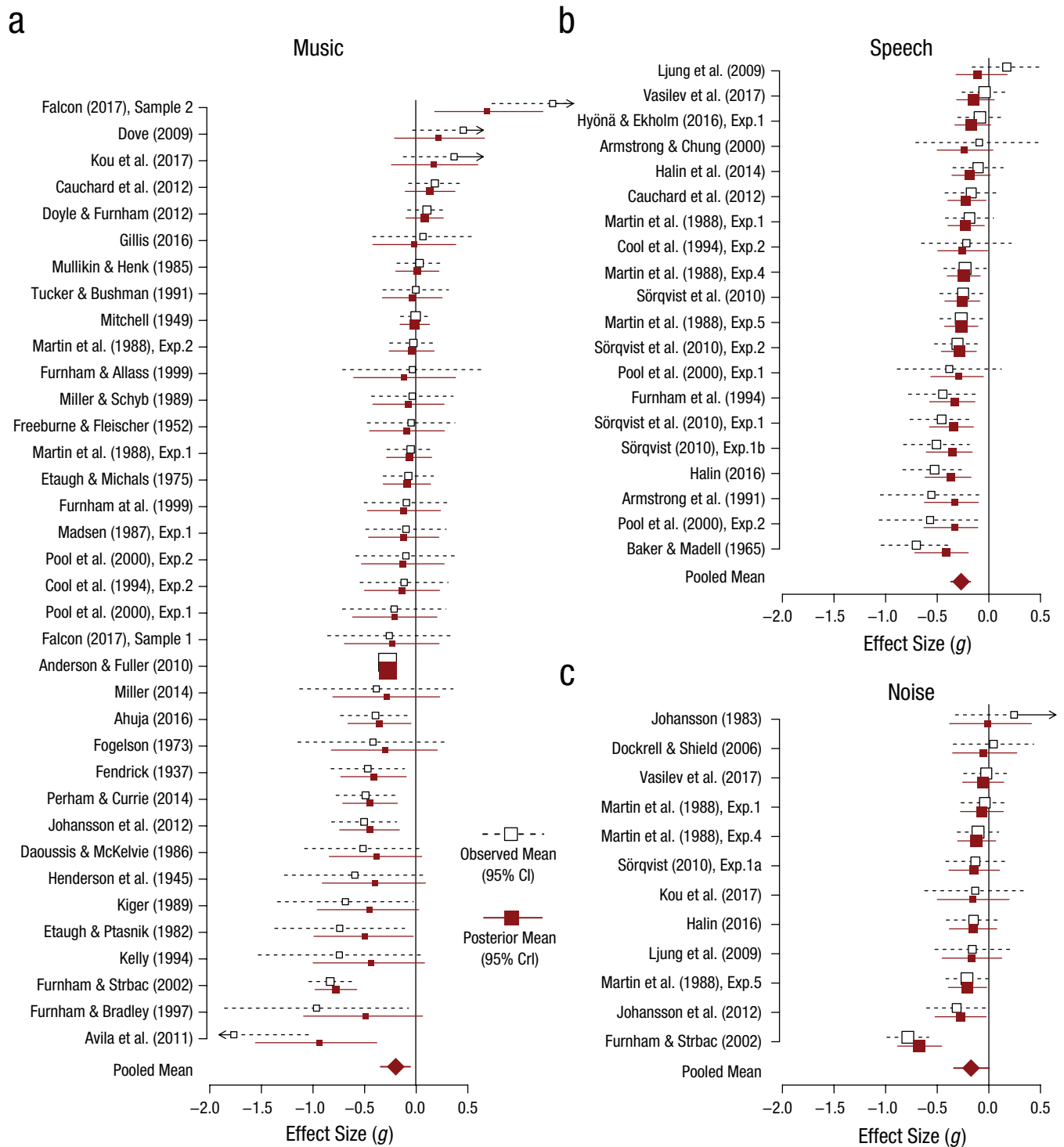


Fig. 4. Forest plot for the main effect of background music (a), speech (b), and noise (c) on reading comprehension. Plotted are the observed (i.e., empirical) effect sizes with their 95% confidence intervals and the posterior effect-size estimates from the meta-analysis model with their corresponding 95% credible intervals. Each square's size is proportional to the weight of the study it represents (i.e., to the inverse of the within-studies variance of the sampling distribution). The red diamond (with 95% credible intervals) at the bottom of each panel indicates the pooled estimate from the meta-analysis.

Table 3. Mean Difference in the Effect Size Between Child and Adult Studies: Metaregression Results

| Analysis | Number of studies | | Mean difference (Hedges's g) | 95% CrI | $p(ES_{CH} > ES_A \mid \text{Data})$ | ESS |
|-----------------------|-------------------|--------|------------------------------------|---------------|--------------------------------------|-------|
| | Children | Adults | | | | |
| Reading comprehension | | | | | | |
| All sounds | 18 | 36 | −0.01 | [−0.10, 0.08] | .43 | 30623 |
| Noise | 5 | 7 | 0.05 | [−0.13, 0.22] | .73 | 29974 |
| Speech | 5 | 15 | 0.00 | [−0.12, 0.12] | .51 | 30263 |
| Music | 13 | 23 | 0.02 | [−0.12, 0.17] | .64 | 18498 |

Note: Mean difference = Posterior estimate of the mean difference (in Hedges's g) between adult and child participants; CrI = credible interval; $p(ES_{CH} > ES_A | \text{Data})$ = probability that the effect size for child participants is bigger than the effect size for adult participants, given the data; ESS = effective sample size of the Markov-chain Monte Carlo chains for the main parameter of interest (β).

As the review of the literature showed, interest in this topic has a very long history that precedes the cognitive revolution and, indeed, most of the work on auditory distraction in other cognitive tasks. Traditionally, much of the interest in auditory distraction in reading tasks has been related to its practical implications for reading outside the psychological laboratory, such as studying for an exam, reading in the classroom, or any kind of work that involves reading in a busy office. However, the inconclusive and sometimes contradictory evidence has made it difficult to arrive at 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 efficiency. Even though the observed cost was modest, especially for measures such as reading speed and proofreading accuracy, there was still relatively high probability that it reflects a true effect in the population. Therefore, the present study resolves some of the controversy highlighted in the introduction by showing that although general auditory-distraction effects by background noise, speech, and music almost certainly exist, their magnitude is small.

Given that there is a 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 possibility is that some of the original studies may not have had sufficient statistical 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 (see Wallisch, 2015). This is for illustrative purposes only, given that statistical power is influenced not only by sample size and the magnitude of the true effect but also by such other factors 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; generally speaking, a larger number of participants are required to achieve sufficient statistical power to detect 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.

Implications for theories of auditory distraction

The second goal of the present study was to investigate what properties of background sounds make them distracting and to test what theoretical frameworks can explain the results. This is an important question, given that not all studies have explicitly considered the theoretical implications of their work; some researchers have taken a more applied approach of simply testing whether certain types of sounds are distracting to readers. More broadly, the present analyses provide a glimpse into how well readers can maintain focus on the main task (reading) while listening to a competing stream of auditory input that they try to ignore. The metaregression results provided a few key insights into the nature of auditory-distraction effects, as measured with reading-comprehension accuracy.

First, lyrical music and intelligible speech were found to be equally distracting, and lyrical music was found to be more distracting than nonlyrical music. Second, intelligible speech was in turn more distracting than unintelligible speech. Finally, environmental noise was more distracting than acoustical noise, but there was no reliable difference between nonlyrical music and acoustical noise. These results provide strong support for the notion that the presence of language in background sounds is the strongest contributor to auditory distraction. Indeed, the two largest distraction effects

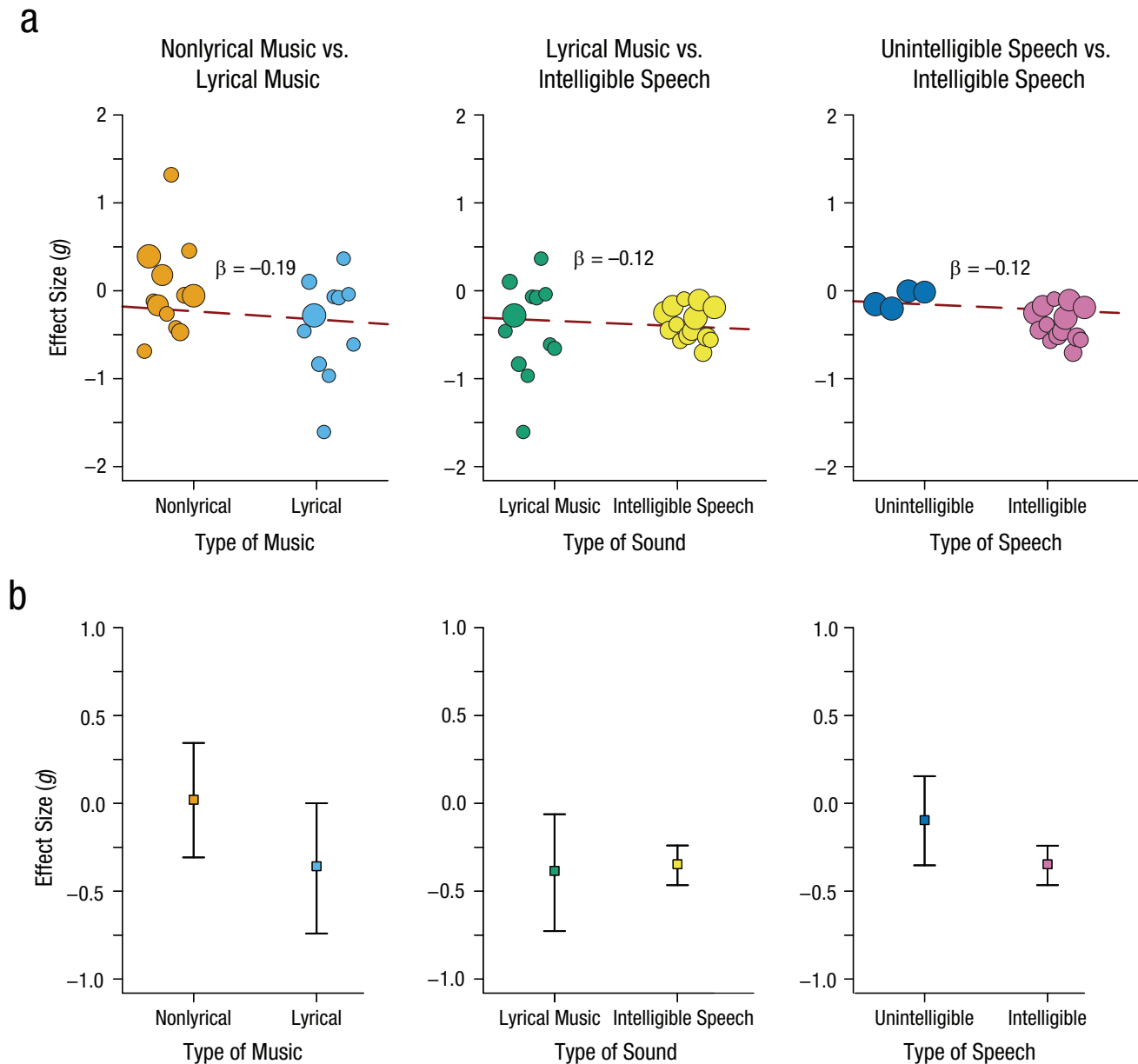


Fig. 5. Results of the metaregression models testing the predictions of the semantic-interference and phonological-interference hypotheses. The graphs in (a) show the regression slopes and the observed effect sizes of the studies included in the analysis. The slope indicates the mean difference between the two groups of studies in each graph, as estimated by the metaregression model. Each circle's size is proportional to the weight of the study it represents (i.e., proportional to the inverse of the within-studies variance of the sampling distribution). The effective sample sizes of the Markov-chain Monte Carlo (MCMC) chains for β are 11,455, 24,381, and 54,689 (from left to right). The graphs in (b) show the estimated posterior effect size for each group of studies from a random-effects meta-analysis of the simple effect. Bars indicate 95% credible intervals. The effective sample sizes of the MCMC chains for θ are 98,478, 95,721, 97,382, 32,748, 15,048, and 34,152 (from left to right).

were found for lyrical music (Hedges's $g = -0.35$) and intelligible speech (Hedges's $g = -0.34$). This last finding is consistent with both the semantic-interference account (Martin et al., 1988) and the interference-by-process account (Marsh et al., 2008), which predict that either the semantic content of spoken or sung lyrics or

the actual process of trying to extract their meaning can distract readers from their main task. Nevertheless, these two accounts cannot explain distraction by non-speech background noise.

The present findings are generally not consistent with the phonological-interference account for two

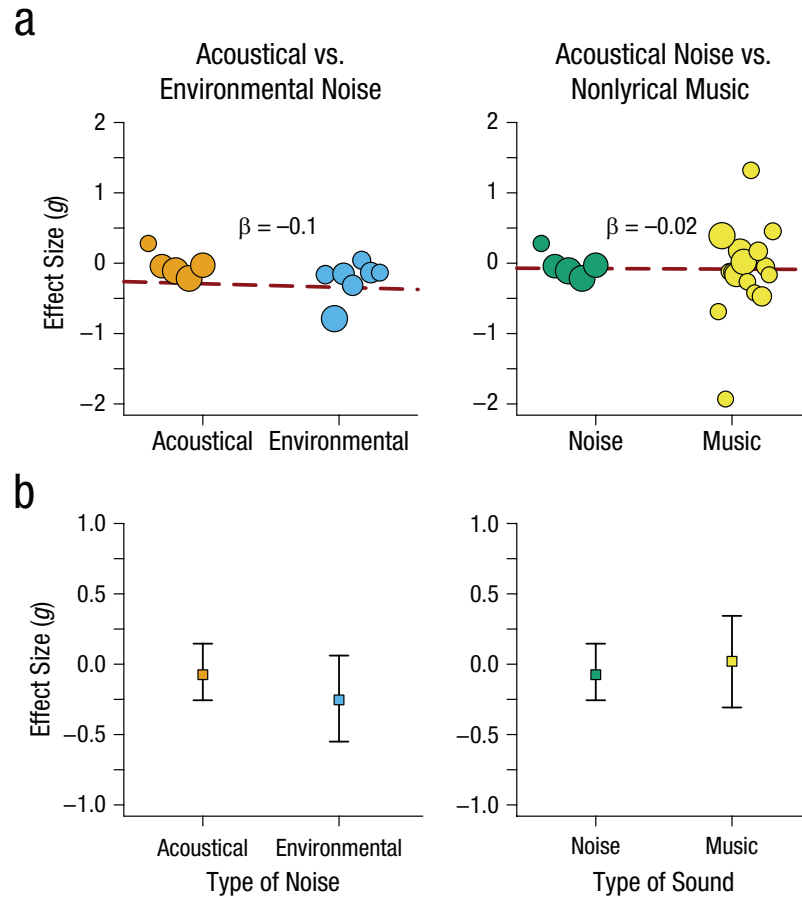


Fig. 6. Results of the metaregression models testing the predictions of the changing-state hypothesis. The graphs in (a) show the regression slope and the observed effect size of the studies included in the analysis. The slope indicates the mean difference between the two groups in each graph, as estimated by the metaregression model. Each circle's size is proportional to the weight of the study it represents (i.e., to the inverse of the within-studies variance of the sampling distribution). The effective sample sizes of the Markov-chain Monte Carlo (MCMC) chains for β are 36,063 (left) and 13,062 (right). The graphs in (b) show the posterior effect size for each group, as estimated by a random-effects meta-analysis of the simple effect. Bars indicate the 95% credible intervals. The effective sample sizes of the MCMC chains for θ are 31,904, 89,200, 31,904, and 98,478 (from left to right).

reasons. First, it predicts that all speech sounds should be equally distracting because they all would gain access to the phonological store; however, intelligible speech was reliably more distracting than unintelligible speech. In addition, background noise, which would not gain access to the phonological store, was also found to cause distraction. Finally, the results are only partially consistent with the changing-state account (Jones et al., 1992), which predicts that sounds with greater acoustic variation would cause greater distraction. This is because environmental noise was more distracting than acoustical noise (which is consistent with the theory), but nonlyrical music was not (which is not consistent with the theory). In both cases, environmental noise and nonlyrical music exhibit more

acoustic variation than acoustical noise (e.g., white or pink noise).

What type of theoretical framework could account for the present results? Clearly, none of the theories considered so far can account for all the findings. Although some theories were successful in accounting for some of the effects, the present results suggest that new theoretical models are needed that can explain all the evidence. This is not necessarily a limitation of existing theoretical accounts because, as noted previously, not all of them were originally designed to account for distraction effects in a reading task. In addition, these theories suggest very useful mechanisms through which auditory distraction can occur. In this sense, it is more useful to consider a hypothetical

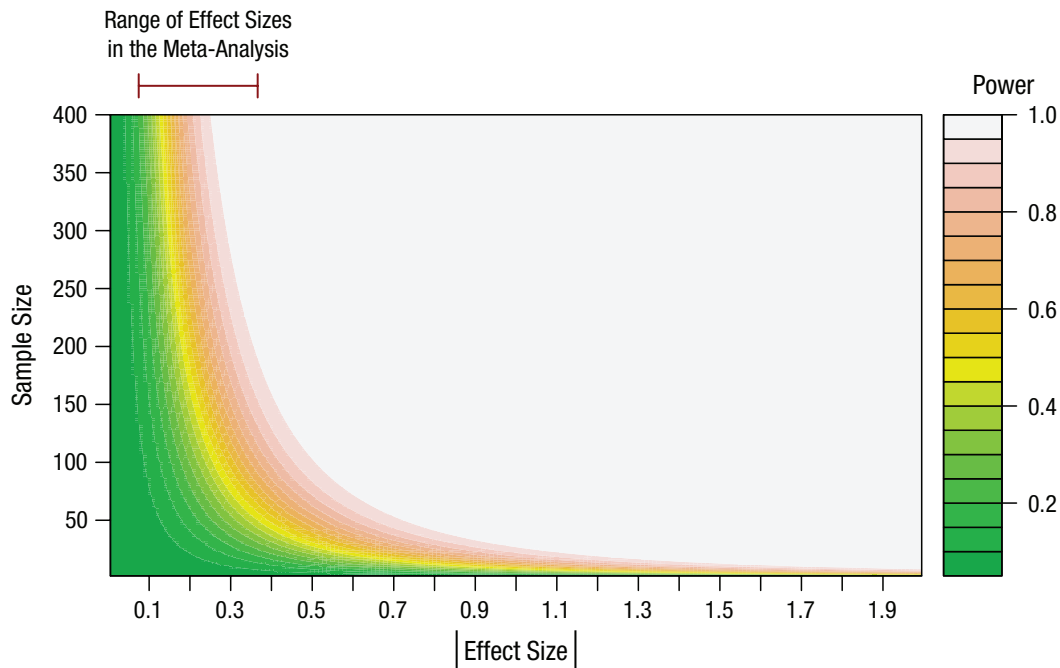


Fig. 7. An illustration of the sample sizes needed to achieve different levels of statistical power for a range of realistic effect sizes. The dark red bracket at the top left shows the range of effect sizes observed in the present meta-analysis. Warmer colors indicate more desirable levels of statistical power. Statistical power was calculated with the *pwr* package (Champely, 2012) for the R software environment (R Core Team, 2016) and is based on an independent-samples, two-tailed *t* test with equal groups at an α level of .05.

model that could explain the data from reading tasks by taking into account the contribution of these theories.

One such framework could be a two-component model in which noise and speech influence reading through separate processes. In the first component, background noise would cause a small decrement in comprehension. The present data cannot fully explain why this disruption by noise occurs, and more research is needed to understand this mechanism. There was some evidence that noise exhibiting greater acoustic variation is associated with greater distraction (see Jones et al., 1992), but other potential mechanisms need to be explored as well. The second component would cause greater decrements in comprehension from intelligible speech (see Marsh et al., 2008; Martin et al., 1988). Recent evidence suggests that the cognitive process of trying to analyze the meaning of the speech may be enough to cause distraction (Hyönä & Ekholm, 2016). Whether the semantic content and semantic representation of the speech sound are processed and cause additional distraction is an open question that needs to be explored in future research. This second component would also account for the effect of background music. This is because the present results suggest that distraction by background music is effectively reduced to

distraction from the sung lyrics, as music without lyrics was not found to be distracting (see Fig. 6b).

The predictions of this model could be further tested through future experimental work. For example, previous research has mostly focused on measuring differences in reading comprehension, but only a few studies so far have used reading speed as a dependent variable, which makes it difficult to evaluate the model on the basis of this measure. However, the two-component model would make the same prediction for reading speed: Background noise should lead to a modest decrease in reading speed, and intelligible background speech should lead to a greater decrease in reading speed because of interference from semantic processing of the speech. Measuring eye movements during reading could also provide a more detailed view of auditory distraction because eye fixations are sensitive to the ongoing cognitive processing of the text (see Rayner, 1998). For example, no studies have yet examined how acoustical or environmental noise may affect fixation durations or fixation probabilities during reading. If the assumption (i.e., that noise results in a small decrease in comprehension accuracy) of the first component of the model is correct, there should also be an increase in either fixation durations or the number of fixations when readers are exposed to noise in the background.

A stronger test of semantic interference by intelligible speech (i.e., the second component of the model) would be to study two participant populations with the same speech sounds. For example, monolingual speakers of French should be distracted by French speech (intelligible), but not by the same speech translated into and spoken in a foreign language, such as German (unintelligible). Conversely, monolingual speakers of German should be distracted by the speech translated into German (intelligible), but not by the original French speech (unintelligible). If the magnitude of auditory distraction by intelligible speech is the same in the two populations, this would provide strong evidence for semantic interference by background speech. In addition, lyrical music has only rarely been used to study distraction due to semantic interference. For example, the proposed model predicts that a lyrical song in the participants' native language would cause distraction because the lyrics are intelligible, whereas the same song in a foreign language would not cause distraction because the lyrics are unintelligible (see Chew, Yu, Chua, & Gan, 2016). Likewise, the model predicts that an instrumental version of the same song would also cause no distraction. Another promising avenue would be to investigate distraction by intelligible speech and lyrical music in second-language learners to determine the role of language proficiency in semantic interference. This could be done by having participants read a text in their native language while listening to background speech in their second language. The second component of the model predicts that distraction will increase as a function of language proficiency because more proficient speakers of the second language would be better at semantically processing the background speech.

Practical implications

The present results also have some practical implications for settings where readers are exposed to distracting background sounds. For example, there is evidence that listening to music when studying or working is commonplace. In one survey, university students reported listening to music 62% of the time when studying or doing homework (David, Kim, Brickman, Ran, & Curtis, 2015). In addition, Calderwood, Ackerman, and Conklin (2014) found that 59% of university students played music in the background when they were asked to study as they normally do. There is also some evidence that listening to music at work is common; 80% of employees report that they listen to music during working hours (Haake, 2006). In this sense, there are many situations in daily life in which people can choose to listen to music while doing reading-related

tasks. The present results have direct implications for reading in educational and work settings because they suggest that listening to lyrical music should be avoided when reading a text for comprehension. This is because lyrical music contains intelligible language in the form of sung lyrics, and this type of music was found to be disruptive to reading comprehension. Instead, readers can avoid this disruption by listening to nonlyrical (i.e., instrumental) music, which does not contain any intelligible language.

In the two-component model outlined above, intelligible lyrical music and intelligible speech are assumed to be equally distracting. In fact, intelligible background speech is often present in many work settings, particularly in open-plan offices and other shared areas that have poor acoustic privacy (e.g., Haapakangas, Hongisto, Eerola, & Kuusisto, 2017; Haapakangas, Hongisto, Hyönä, Kokko, & Keränen, 2014; Schlittmeier & Liebl, 2015). The present results suggest that intelligible speech is likely to impair performance on office tasks that require reading for comprehension, proofreading, or processing the meaning of written information. Because of this, limiting the amount of intelligible speech in open-plan offices is likely to improve reading performance among office workers. If this is difficult to achieve for practical reasons, acoustically masking the background speech (e.g., with natural sounds) might be helpful because this will decrease its intelligibility and therefore its negative impact (Haapakangas et al., 2011; Jahncke, Björkeholm, Marsh, Odelius, & Sörqvist, 2016; see also Hongisto, 2005). Furthermore, the present results and the proposed model also suggest that readers exposed to background noise will likely incur a modest cost in terms of reduced comprehension. This suggests that external environmental noise should be limited in settings in which reading is common, such as in schools or in libraries. Finally, the practical implications of the present findings would apply equally to adults and children because the two groups did not generally differ in terms of auditory distraction during reading.

Limitations

Although metaregression is a very useful tool for testing how auditory distraction differs between background sounds or age groups, the present results are only observational in nature (S. G. Thompson & Higgins, 2002). Therefore, direct evidence from laboratory experiments and direct comparisons of the different factors are required to verify these results. Nevertheless, we anticipate that our findings, which are based on all the available evidence, will prove to be very useful in guiding future experimental research and advancing

our theoretical understanding of how auditory distraction during reading occurs.

In addition, some of the metaregression analyses were performed on a small number of studies. However, this is not necessarily a limitation in the Bayesian approach that we have adopted here because the results simply reflect our best understanding of auditory-distraction effects given the currently available data. Once more data are available, the present results can be easily updated via Bayes' theorem, which will lead to an even more precise estimate of the effects.

Future directions

The present study grouped background sounds into broad categories, such as noise, speech, or music. However, real-word sounds to which readers are routinely exposed do not always belong to only one of these categories. Rather, different sounds may be present at the same time, such as music playing from a TV, background speech from a nearby conversation, and environmental noise from nearby traffic. Currently, there is a limited understanding of how different types of sounds may interact to increase or decrease distraction. For example, there is some evidence that acoustical noise intermixed with background speech can reduce the negative impact of the speech sound by reducing its intelligibility (Haapakangas et al., 2011; Hongisto, 2005; Venetjoki et al., 2006). Therefore, more research is needed to investigate sounds that are more complex and thus more representative of auditory distraction in the real world. In addition, previous research has not investigated the behavioral aspects of auditory distraction: For example, can participants' motivation and goals influence how distracted they are by different background sounds during reading?

Another question that deserves more attention is how auditory distraction may differ between age groups. Studies with adults and children have usually been done in isolation, which makes it challenging to assess how these groups differ under the same experimental conditions. The present metaregression analyses are arguably the only possible way of addressing this question with the currently available data. However, experiments directly comparing adults and children are needed to make firm conclusions. Traditionally, a great deal of research has focused on large-scale epidemiological studies of long-term exposure to noise in schools, such as the Road traffic and Aircraft Noise exposure and Children's cognition and Health study (RANCH; Stansfeld et al., 2005) and the West London study (Haines, Stansfeld, Brentnall, et al., 2001; Haines, Stansfeld, Job, et al., 2001a; Haines, Stansfeld, Job, et al., 2001b). Because of this, surprisingly little is

known about the effect of experimental exposure to noise on reading in children. Eye-movement recordings may be particularly helpful in studying this topic because they can reveal subtle auditory-distraction effects that may not appear in behavioral measures such as comprehension accuracy (Cauchard et al., 2012; Hyönä & Ekholm, 2016; Yan et al., 2017). Longitudinal studies of reading development have already made successful use of eye tracking to study such processes as the development of the perceptual span (Sperlich, Meixner, & Laubrock, 2016), and this method also holds promise in understanding how children's susceptibility to distraction may change during the school years and beyond.

Eye-tracking technology and event-related-potential recordings are useful methods because they can provide rich data about the time course of auditory-distraction effects during reading. We anticipate that this type of evidence will be crucial for gaining a better understanding of when and how these effects occur and what their theoretical nature is. The field of eye movements during silent reading has already seen the successful development of advanced computational models such as the E-Z Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998) and SWIFT (Engbert et al., 2005), which can simulate many empirical findings. Likewise, a more precise quantification of the time course of auditory-distraction effects can move the field forward by making it possible to build computational models that can simulate these processes and to generate new predictions.

Conclusion

Auditory distraction during reading has been a topic of interest for the past 80 years and, as the surge of recent publications shows, it is likely to continue to be an active area of research in the future. The present study was the first attempt to make a comprehensive statistical synthesis of auditory-distraction effects in a reading task. The results showed that background noise, speech, and music are almost always distracting, even if the distraction effects are often small in size. Sounds that contain intelligible language (i.e., speech or lyrical music) were particularly distracting, most likely because of their semantic properties that interfere with processing the written text. The present findings also have some practical implications. For example, they suggest that listening to instrumental music while reading does not affect the comprehension of the text, whereas listening to lyrical music does. In addition, readers exposed to background noise are likely to incur a cost in terms of reduced comprehension, even if this cost is very small. Finally, the recent interest in measuring eye

movements during reading in the presence of background auditory input heralds the emergence of a new subfield that may give an even more precise understanding of how and when auditory distraction occurs.

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 long-term 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 counterbalancing 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 content 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 min).
- The comprehension assessment was done in silence.

Appendix B

Table B1. A Summary of the Studies That Were Included in the Meta-Analysis and Their Effect Sizes

| Study | N_C | N_E | Samp | Des | DV | Sound | Sound type | Db(A) | g | Var |
|-------------------------------|-------|-------|------|-----|----|-------|------------------------|-------|-------|------|
| Sörqvist, Halin, et al., 2010 | 40 | | A | W | RC | S | Native | 72.5 | -0.24 | 0.01 |
| Sörqvist, Halin, et al., 2010 | 40 | | A | W | RS | S | Native | 72.5 | -0.05 | 0.01 |
| Ljung et al., 2009 | 70 | 50 | C | B | RC | N | Traffic | 62 | -0.16 | 0.03 |
| Ljung et al., 2009 | 70 | 50 | C | B | RS | N | Traffic | 62 | 0.71 | 0.04 |
| Ljung et al., 2009 | 70 | 66 | C | B | RC | S | Babble | 62 | 0.17 | 0.03 |
| Ljung et al., 2009 | 70 | 66 | C | B | RS | S | Babble | 62 | 0.21 | 0.03 |
| Fogelson, 1973 | 14 | 14 | C | B | RC | M | Pop | — | -0.42 | 0.14 |
| Tucker & Bushman, 1991 | 75 | 76 | A | B | RC | M | Rock & roll | 80 | 0.00 | 0.03 |
| Daoussis & McKelvie, 1986 | 24 | 24 | A | B | RC | M | Rock | 50 | -0.52 | 0.08 |
| Etaugh & Michals, 1975 | 32 | | A | W | RC | M | Preferred | — | -0.08 | 0.02 |
| Etaugh & Ptasnik, 1982 | 20 | 20 | A | B | RC | M | Preferred | — | -0.74 | 0.10 |
| Kiger, 1989 | 18 | 18 | C | B | RC | M | Low load | — | 3.50 | 0.28 |
| Kiger, 1989 | 18 | 18 | C | B | RC | M | High load | — | -0.69 | 0.11 |
| L. K. Miller & Schyb, 1989 | 49 | 49 | A | B | RC | M | Classical | 47.5 | 0.11 | 0.04 |
| L. K. Miller & Schyb, 1989 | 49 | 49 | A | B | RC | M | Pop | 47.5 | 0.23 | 0.04 |
| L. K. Miller & Schyb, 1989 | 49 | 49 | A | B | RC | M | Vocal | 47.5 | -0.46 | 0.04 |
| Doyle & Furnham, 2012 | 56 | | A | W | RC | M | Vocal | — | 0.10 | 0.01 |
| Anderson & Fuller, 2010 | 334 | | C | W | RC | M | Lyrical | 75 | -0.28 | 0.00 |
| Furnham & Strbac, 2002 | 76 | | C | W | RC | N | Office | — | -0.78 | 0.01 |
| Furnham & Strbac, 2002 | 76 | | C | W | RC | M | Vocal/unfamiliar | — | -0.83 | 0.01 |
| Mullikin & Henk, 1985 | 45 | | C | W | RC | M | Classical | — | 0.39 | 0.01 |
| Mullikin & Henk, 1985 | 45 | | C | W | RC | M | Rock | — | -0.33 | 0.01 |
| Avila et al., 2011 | 19 | 20 | C | B | RC | M | Vocal/ familiar | — | -1.61 | 0.13 |
| Avila et al., 2011 | 19 | 19 | C | B | RC | M | Instrumental/ familiar | — | -1.93 | 0.15 |
| Freeburne & Fleischer, 1952 | 43 | 46 | A | B | RC | M | Classical | — | 0.02 | 0.04 |

(continued)

Table B1. (Continued)

| Study | N_C | N_E | Samp | Des | DV | Sound | Sound type | Db(A) | g | Var |
|-----------------------------|-------|-------|------|-----|----|-------|---------------------------|-------|-------|------|
| Freeburne & Fleischer, 1952 | 43 | 46 | A | B | RS | M | Classical | — | -0.35 | 0.04 |
| Freeburne & Fleischer, 1952 | 43 | 42 | A | B | RC | M | Pop | — | 0.04 | 0.05 |
| Freeburne & Fleischer, 1952 | 43 | 42 | A | B | RS | M | Pop | — | -0.40 | 0.05 |
| Freeburne & Fleischer, 1952 | 43 | 40 | A | B | RC | M | Semiclassical | — | -0.08 | 0.05 |
| Freeburne & Fleischer, 1952 | 43 | 40 | A | B | RS | M | Semiclassical | — | -0.36 | 0.05 |
| Freeburne & Fleischer, 1952 | 43 | 37 | A | B | RC | M | Jazz | — | -0.17 | 0.05 |
| Freeburne & Fleischer, 1952 | 43 | 37 | A | B | RS | M | Jazz | — | -0.61 | 0.05 |
| Fendrick, 1937 | 61 | 62 | A | B | RC | M | Semiclassical | — | -0.47 | 0.03 |
| Henderson et al., 1945 | 19 | 17 | A | B | RC | M | Classical | — | -0.12 | 0.11 |
| Henderson et al., 1945 | 19 | 14 | A | B | RC | M | Pop | — | -1.07 | 0.14 |
| C. Miller, 2014 | 13 | 13 | A | B | RC | M | Classical lyrical | — | -0.84 | 0.16 |
| C. Miller, 2014 | 13 | 17 | A | B | RC | M | Classical instrumental | — | 0.13 | 0.13 |
| C. Miller, 2014 | 13 | 11 | A | B | RC | M | Rock lyrical | — | -0.38 | 0.16 |
| C. Miller, 2014 | 13 | 18 | A | B | RC | M | Rock instrumental | — | -0.45 | 0.13 |
| Furnham & Allass, 1999 | 16 | 16 | A | B | RC | M | Complex | — | -0.02 | 0.12 |
| Furnham & Allass, 1999 | 16 | 16 | A | B | RC | M | Simple | — | -0.05 | 0.12 |
| Furnham & Bradley, 1997 | 10 | 10 | A | B | RC | M | Pop | — | -0.97 | 0.21 |
| Furnham et al., 1999 | 43 | 49 | C | B | RC | M | Instrumental | — | -0.12 | 0.04 |
| Furnham et al., 1999 | 43 | 47 | C | B | RC | M | Vocal | — | -0.07 | 0.04 |
| Perham & Currie, 2014 | 30 | | A | W | RC | M | Disliked lyrical | 70 | -0.71 | 0.02 |
| Perham & Currie, 2014 | 30 | | A | W | RC | M | Nonlyrical | 70 | -0.16 | 0.02 |
| Perham & Currie, 2014 | 30 | | A | W | RC | M | Liked lyrical | 70 | -0.60 | 0.02 |
| Kelly, 1994 | 13 | 12 | A | B | RC | M | Pop | 65 | -0.74 | 0.16 |
| Dove, 2009 | 28 | 28 | A | B | RC | M | Sedative classical | 62.5 | 0.10 | 0.07 |
| Dove, 2009 | 28 | 28 | A | B | RC | M | Stimulating classical | 62.5 | 0.81 | 0.08 |
| Dove, 2009 | 28 | 28 | A | B | RS | M | Sedative classical | 62.5 | -0.07 | 0.07 |
| Dove, 2009 | 28 | 28 | A | B | RS | M | Stimulating classical | 62.5 | -0.51 | 0.07 |
| Furnham et al., 1994 | 20 | | A | W | RC | S | TV drama | — | -0.45 | 0.03 |
| C. R. Johansson, 1983 | 22 | 22 | C | B | RC | N | Continuous | 51 | 0.28 | 0.09 |
| C. R. Johansson, 1983 | 22 | 22 | C | B | RC | N | Intermittent | 67.4 | 0.21 | 0.09 |
| Halin, 2016 | 28 | | A | W | RC | S | Native (easy) | 60 | -0.89 | 0.03 |
| Halin, 2016 | 28 | | A | W | RC | S | Native (difficult) | 60 | -0.16 | 0.02 |
| Halin, 2016 | 28 | | A | W | RC | N | Traffic (easy) | 60 | -0.35 | 0.02 |
| Halin, 2016 | 28 | | A | W | RC | N | Traffic (difficult) | 60 | -0.01 | 0.02 |
| Halin, 2016 | 28 | | A | W | RC | N | Aircraft (easy) | 60 | -0.23 | 0.02 |
| Halin, 2016 | 28 | | A | W | RC | N | Aircraft (difficult) | 60 | -0.01 | 0.02 |
| Smith-Jackson & Klein, 2009 | 54 | | A | W | PR | S | Native | 65 | -0.04 | 0.01 |
| Cauchard et al., 2012 | 30 | | A | W | RC | M | Instrumental | 65 | 0.18 | 0.02 |
| Cauchard et al., 2012 | 30 | | A | W | RC | S | Native | 65 | -0.17 | 0.02 |
| Cauchard et al., 2012 | 30 | | A | W | RS | M | Instrumental | 65 | 0.01 | 0.02 |
| Cauchard et al., 2012 | 30 | | A | W | RS | S | Native | 65 | -0.20 | 0.02 |
| R. Johansson et al., 2012 | 24 | | A | W | RC | M | Preferred | 65 | -0.34 | 0.02 |
| R. Johansson et al., 2012 | 24 | | A | W | RC | M | Nonpreferred | 65 | -0.67 | 0.03 |
| R. Johansson et al., 2012 | 24 | | A | W | RC | N | Cafe | 65 | -0.31 | 0.02 |
| R. Johansson et al., 2012 | 24 | | A | W | RS | M | Preferred | 65 | -0.14 | 0.02 |
| R. Johansson et al., 2012 | 24 | | A | W | RS | M | Nonpreferred | 65 | -0.10 | 0.02 |

(continued)

Table B1. (Continued)

| Study | N_C | N_E | Samp | Des | DV | Sound | Sound type | Db(A) | g | Var |
|--|-------|-------|------|-----|-----------------|-------|---------------------------------------|-------|-------|------|
| R. Johansson et al., 2012 | 24 | | A | W | RS | N | Cafe | 65 | -0.07 | 0.02 |
| Weinstein, 1974 | 15 | 18 | A | B | PR ^a | N | Teletype | 70 | -0.56 | 0.12 |
| Weinstein, 1974 | 15 | 18 | A | B | PR ^b | N | Teletype | 70 | -1.26 | 0.14 |
| Weinstein, 1977 | 29 | | A | W | PR ^a | S | Native | 68 | -0.03 | 0.02 |
| Weinstein, 1977 | 29 | | A | W | PR ^b | S | Native | 68 | -0.29 | 0.02 |
| Martin et al., 1988, E1 | 36 | | A | W | RC | S | Native | 82 | -0.20 | 0.01 |
| Martin et al., 1988, E1 | 36 | | A | W | RC | S | Random | 82 | -0.18 | 0.01 |
| Martin et al., 1988, E1 | 36 | | A | W | RC | M | Instrumental | 82 | 0.00 | 0.01 |
| Martin et al., 1988, E1 | 36 | | A | W | RC | M | Random tones | 82 | -0.11 | 0.01 |
| Martin et al., 1988, E1 | 36 | | A | W | RC | N | White | 82 | -0.04 | 0.01 |
| Martin et al., 1988, E2 | 36 | | A | W | RC | M | Instrumental | 82 | 0.02 | 0.01 |
| Martin et al., 1988, E2 | 36 | | A | W | RC | M | Lyrical | 82 | -0.08 | 0.01 |
| Martin et al., 1988, E4 | 48 | | A | W | RC | N | White | 82 | -0.11 | 0.01 |
| Martin et al., 1988, E4 | 48 | | A | W | RC | S | Native | 82 | -0.31 | 0.01 |
| Martin et al., 1988, E4 | 48 | | A | W | RC | S | Foreign | 82 | -0.15 | 0.01 |
| Martin et al., 1988, E5 | 48 | | A | W | RC | N | White | 82 | -0.21 | 0.01 |
| Martin et al., 1988, E5 | 48 | | A | W | RC | S | Nonword | 82 | -0.20 | 0.01 |
| Martin et al., 1988, E5 | 48 | | A | W | RC | S | Random words | 82 | -0.33 | 0.01 |
| Cool et al., 1994, E2 | 9 | | C | W | RS | M | Radio/generic | — | 0.13 | 0.05 |
| Cool et al., 1994, E2 | 9 | | C | W | RS | S | Movies | — | 0.20 | 0.05 |
| Cool et al., 1994, E2 | 9 | | C | W | RC | M | Radio/generic | — | -0.12 | 0.05 |
| Cool et al., 1994, E2 | 9 | | C | W | RC | S | Movies | — | -0.22 | 0.05 |
| Mitchell, 1949 | 91 | | C | W | RTS | M | Radio/generic | — | -0.01 | 0.01 |
| Armstrong et al., 1991 | 33 | 30 | A | B | RTS | S | TV ads | — | -0.63 | 0.07 |
| Armstrong et al., 1991 | 33 | 32 | A | B | RTS | S | TV drama | — | -0.48 | 0.06 |
| Pool et al., 2000, E1 | 30 | 30 | C | B | RC | S | TV soap opera | 60 | -0.38 | 0.07 |
| Pool et al., 2000, E1 | 30 | 30 | C | B | RC | M | TV music | 60 | -0.21 | 0.07 |
| Pool et al., 2000, E2 | 48 | 24 | C | B | RC | S | TV soap opera | 60 | -0.57 | 0.06 |
| Pool et al., 2000, E2 | 48 | 24 | C | B | RC | M | TV music | 60 | -0.10 | 0.06 |
| Dockrell & Shield, 2006 | 52 | 52 | C | B | RTS | N | Babble | 65 | -0.49 | 0.04 |
| Dockrell & Shield, 2006 | 52 | 52 | C | B | RTS | N | Babble/ environmental | 65 | 0.58 | 0.04 |
| Hyönä & Ekholm, 2016, E1 | 42 | | A | W | RC | S | Native | 82.5 | -0.17 | 0.01 |
| Hyönä & Ekholm, 2016, E1 | 42 | | A | W | RC | S | Foreign | 82.5 | 0.00 | 0.01 |
| Hyönä & Ekholm, 2016, E1 | 42 | | A | W | RS | S | Native | 82.5 | -0.02 | 0.01 |
| Hyönä & Ekholm, 2016, E1 | 42 | | A | W | RS | S | Foreign | 82.5 | 0.06 | 0.01 |
| Hyönä & Ekholm, 2016, E2 | 36 | | A | W | RS | S | Scrambled- different | 82.5 | -0.15 | 0.01 |
| Hyönä & Ekholm, 2016, E2 | 36 | | A | W | RS | S | Scrambled-same | 82.5 | -0.18 | 0.01 |
| Hyönä & Ekholm, 2016, E3 | 35 | | A | W | RS | S | Native | 82.5 | -0.13 | 0.01 |
| Hyönä & Ekholm, 2016, E3 | 35 | | A | W | RS | S | Scrambled | 82.5 | -0.20 | 0.01 |
| Hyönä & Ekholm, 2016, E4 | 36 | | A | W | RS | S | Scrambled: semantic | 82.5 | -0.11 | 0.01 |
| Hyönä & Ekholm, 2016, E4 | 36 | | A | W | RS | S | Scrambled: syntactic + semantic | 82.5 | -0.14 | 0.01 |
| Armstrong & Chung, 2000 | 19 | 20 | A | B | RC | S | Native | — | -0.09 | 0.10 |
| Madsen, 1987, E1 | 50 | 50 | A | B | RC | M | Various | 75 | -0.10 | 0.04 |
| Sörqvist, 2010a, E1a | 23 | | C | W | RC | N | Aircraft | 57.5 | -0.13 | 0.02 |
| Sörqvist, 2010a, E1b | 23 | | C | W | RC | S | Native | 57.5 | -0.51 | 0.03 |
| Sörqvist, Ljungberg, et al., 2010, E1 | 24 | | A | W | RC | S | Native | 65 | -0.46 | 0.02 |

(continued)

Table B1. (Continued)

| Study | N_C | N_E | Samp | Des | DV | Sound | Sound type | Db(A) | g | Var |
|---------------------------------------|-------|-------|------|-----|-----------------|-------|-----------------|-------|-------|------|
| Sörqvist, Ljungberg, et al., 2010, E2 | 42 | | A | W | RC | S | Native | 65 | -0.30 | 0.01 |
| Halin, Marsh, Haga, et al., 2014 | 32 | | A | W | RC | S | Native | 65 | -0.10 | 0.02 |
| Halin, Marsh, Haga, et al., 2014, E1 | 31 | | A | W | PR ^b | S | Native | 65 | -0.09 | 0.02 |
| Halin, Marsh, Haga, et al., 2014, E1 | 31 | | A | W | PR ^a | S | Native | 65 | 0.20 | 0.02 |
| Halin, Marsh, Haga, et al., 2014, E2 | 29 | | A | W | PR ^b | S | Native | 65 | -0.13 | 0.02 |
| Halin, Marsh, Haga, et al., 2014, E2 | 29 | | A | W | PR ^a | S | Native | 65 | 0.11 | 0.02 |
| Haapakangas et al., 2011 | 54 | | A | W | PR ^b | S | Native | 48 | -0.09 | 0.01 |
| Haapakangas et al., 2011 | 54 | | A | W | PR ^a | S | Native | 48 | -0.11 | 0.01 |
| Baker & Madell, 1965 | 24 | | A | W | RC | S | Native | — | -0.70 | 0.03 |
| Vasilev et al., 2017 | 40 | | A | W | RC | N | Speech spectrum | 60 | -0.03 | 0.01 |
| Vasilev et al., 2017 | 40 | | A | W | RC | S | Foreign | 60 | -0.01 | 0.01 |
| Vasilev et al., 2017 | 40 | | A | W | RC | S | Native | 60 | -0.07 | 0.01 |
| Vasilev et al., 2017 | 40 | | A | W | RS | N | Speech spectrum | 60 | 0.04 | 0.01 |
| Vasilev et al., 2017 | 40 | | A | W | RS | S | Foreign | 60 | -0.06 | 0.01 |
| Vasilev et al., 2017 | 40 | | A | W | RS | S | Native | 60 | -0.15 | 0.01 |
| Falcon, 2017, Sample 1 | 22 | 20 | C | B | RC | M | Classical | 55 | -0.26 | 0.09 |
| Falcon, 2017, Sample 2 | 25 | 28 | C | B | RC | M | Classical | 55 | 1.32 | 0.09 |
| Ahuja, 2016 | 20 | | A | W | RC | M | Liked | 60 | -0.71 | 0.04 |
| Ahuja, 2016 | 20 | | A | W | RC | M | Disliked | 60 | -0.08 | 0.02 |
| Kou et al., 2017 | 31 | 29 | A | B | RC | M | Pop vocal | 65 | 0.37 | 0.07 |
| Kou et al., 2017 | 31 | 32 | A | B | RC | N | Office | 65 | -0.13 | 0.06 |
| Sukowski & Romanus, 2016 | 12 | | A | W | PR | S | Native | 59.5 | -0.62 | 0.05 |
| Yan et al., 2017 | 42 | | A | W | RS | S | Native | 62 | -0.16 | 0.01 |
| Yan et al., 2017 | 42 | | A | W | RS | S | Meaningless | 62 | 0.06 | 0.01 |
| Gillis, 2016 | 24 | 47 | A | B | RC | M | Various | — | 0.07 | 0.06 |

Note: N_C = number of participants in the control (silence) condition; N_E = number of participants in the experimental (sound) condition; RC = Reading comprehension; RS = reading speed; RTS = reading test score; PR = proofreading accuracy; g = Hedges's g (effect size).

^aNoncontextual errors (proofreading accuracy). ^bContextual errors (proofreading accuracy).

Action Editor

Timothy McNamara served as action editor for this article; Robert J. Sternberg served as editor-in-chief.

Acknowledgments

Bournemouth University had no role in the design, analysis, or the writing of this article or decisions to publish. All data analysis scripts and materials are available via the Open Science Framework and can be accessed at <https://osf.io/6frzn/>

ORCID iD

Martin Rachev Vasilev  <https://orcid.org/0000-0003-1944-8828>

Declaration of Conflicting Interests

The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

Funding

M. R. Vasilev was supported by a PhD studentship from Bournemouth University.

Notes

1. It should be noted that the amount of semantic content may differ depending on the type of music. Nevertheless, the lyrical music examined in this analysis also contained instrumental sections that had no lyrics. This was determined by listening to the music that was played in the original studies. Therefore, even though lyrics were present in the music, this was not the case for the whole duration of the song.

2. Four studies did not contain any information that made it possible to calculate the effect sizes. Because 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 toward the number of included studies). We explored the implications of this through statistical simulations

and found no evidence that failing to include these studies biased the results (see the Supplemental Material).

3. One exception was the metaregression model comparing lyrical and nonlyrical music. We show in the Supplemental Material that the way the effect sizes were chosen did not influence the conclusions from this analysis.

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