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Review

The consequences of tinnitus and tinnitus severity on cognition: A review of the behavioural evidence

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People with tinnitus report anecdotal difficulties in mental concentration and psychological treatments for tinnitus advise on concentration difficulties and how to manage them. Yet the literature lacks any coherent discussion about what precise theoretical cognitive constructs might be mediating reported concentration problems. This review addresses this gap by describing and critically appraising the behavioural evidence for the effects of tinnitus on cognitive performance (namely working memory and attention). Empirical evidence is somewhat limited, but there is some support that tinnitus interferes with executive attention, and mixed support that it impairs working memory and selective attention. We highlight a number of methodological considerations to help drive the field forward and we propose a putative model of the complex inter-relationships between tinnitus, cognition and confounding factors. This model provides a basis for hypothesis testing.

Contents

1. Introduction

There is a body of clinical evidence that people with tinnitus report anecdotal difficulties in mental concentration (Tyler and

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Baker, 1983; Sanchez and Stephens, 1997; Andersson et al., 1999). In terms of clinical management for tinnitus, psychological approaches advise on concentration difficulties and how to manage them (Abbott et al., 2009; Andersson, 2001; Andersson and Kaldo, 2004; Andersson et al., 2002; Kaldo et al., 2007; Kaldo-Sandström et al., 2004). Many tinnitus questionnaires ask about ability to concentrate, to think clearly or to focus on other things apart from tinnitus (e.g. Meikle et al., 2012). A dedicated tinnitus questionnaire has recently been developed to specify the degree of cognitive ‘failures and mishaps’ that are relevant to performing adequately in daily life (Bankstahl and Görtelmeyer, 2013). This instrument has not yet gained widespread use. An earlier tool (the Cognitive Failures Questionnaire, Broadbent et al., 1982) has been used in tinnitus research (e.g. McKenna et al., 1995; McKenna and Hallam, 1999), but this tool has been criticized for its limited use as a standard measure in clinical practice (Wagle et al., 1999). In particular, psychologists have noted that the accuracy of an individual's self-assessment of his/her own abilities alters radically with age-related changes in self-regard and in life-style (Rabbit and Abson, 1991), and this might also be relevant for self-assessment of mental concentration in older adults with tinnitus. Whether or not self-reported everyday cognitive slips and errors are more common in people with tinnitus, and not simply a general reflection of ageing, is contradictory (Bankstahl and Görtelmeyer, 2013; McKenna et al., 1995; McKenna and Hallam, 1999; Rossiter et al., 2006). Moreover, audiologists have noted that people with tinnitus often attribute hearing problems to the tinnitus itself (Henry et al., 2015). In other words, complaints about concentration *may* be caused by difficulties in listening and communicating, not due to tinnitus per se (see McKenna and Hallam, 1999).

While a concept such as ‘concentration’ is a lay person's label for his/her personal experience, scientific studies of exactly how cognition is affected by tinnitus are needed to explain clinical findings and to better understand the impact of tinnitus severity on cognitive impairment. This review focuses on working memory and attention because these are the most relevant theoretical constructs for cognition. Cognitive psychologists have examined theories/models of working memory and attention largely based on experiments under controlled, scientific conditions that reduce cognition to its basic constituents (Eysenck and Keane, 2015). While these experiments may lack ecological validity, their advantage lies in identifying what specific elements of cognition might mediate the self-reported lapses in concentration.

A review of contemporary behavioural evidence is warranted. To our knowledge, the only dedicated review of this topic was published almost 10 years ago (Andersson and McKenna, 2006) and the authors concluded: “In sum, the published evidence so far concerning the disruption of information processing is relatively weak” (pp 40). Our review brings several unique features. Not only does it consider behavioural evidence in the context of well-established psychological models of cognition, it also examines the evidence for linking it back to anecdotal clinical observation. The primary aim of our review is to summarise and critically appraise behavioural research that addresses the impact of tinnitus and tinnitus severity on various aspects of working memory and attention. We do not review studies using challenging tasks in which it is not possible to separate out the contributions of many different components of cognitive processing (e.g. Acrani and Pereira, 2010; Pierce et al., 2012; the Vienna Determination Task in Jackson et al., 2014). On occasion we may use different terminology from the authors to describe what cognitive constituent each task addresses because we present the body of knowledge according to well-established models (see Sections 4 and 5, respectively). A secondary objective is to examine whether studies have considered how impaired cognitive performance relates to those people with tinnitus who actually report concentration difficulties or cognitive failures and mishaps. Third, we appraise the included studies for important aspects of risk of bias in order to make general recommendations for future research. We end by proposing a testable cognitive model that is a synthesis of the research literature considered within this article.

2. Identification and selection of publications

The peer-reviewed literature was searched using the PubMed electronic database which includes Medline. To identify articles examining the effect of tinnitus and tinnitus severity on specific components of working memory and attention, the search was: ((((tinnitus[Title]) AND cogniti*[Title])) OR ((tinnitus[Title]) AND attention[Title])) OR ((tinnitus[Title]) AND memory[Title]), with records filtered for a publication date on or after 1990, English language and restricted to humans. The date of 1990 was chosen as it corresponded to the landmark publication by Posner and Petersen (1990) presenting a psychological model of attention. This search returned 65 records in total, with 3 further records identified after a hand search of the two reviews (Andersson and McKenna, 2006; Roberts et al., 2013) within the original list of 65. This gave 68 potentially eligible records. Fifty-nine records were excluded because they were out of scope (see Fig. 1), leaving 9 records for review.

For each of the included records, Sections 3 and 4 presents a narrative synthesis describing the participant groups, cognitive tests administered and the findings as they relate to our primary objective. Section 5 gathers the evidence for the link between

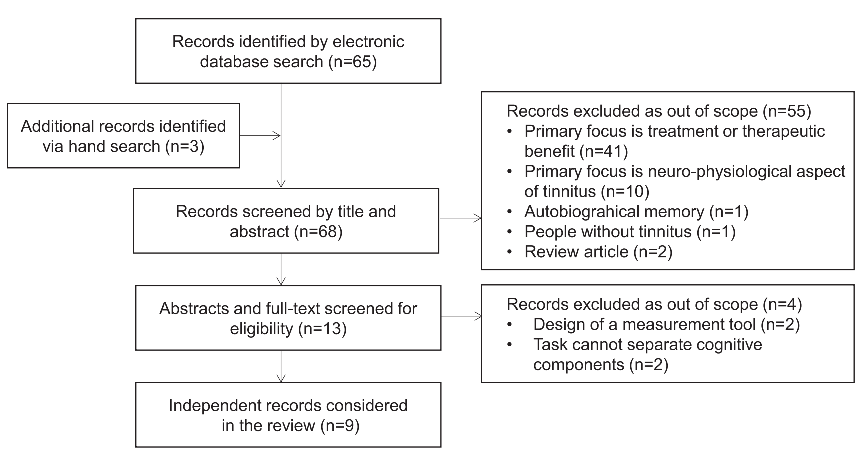

Fig. 1. Flow diagram of study selection.

impaired cognitive performance and reported everyday concentration or memory difficulties, thus addressing our secondary objective. While we are interested in the effect of tinnitus on specific aspects of cognitive performance, one must remain aware of what other factors may modify the observed findings because these can cause a reported association (or lack thereof) to be misleading. Potential biases were examined using a risk-of-bias checklist to make a judgement about the extent to which results of the included studies should be believed (Higgins and Green, 2011: pp. 189). Section 6 presents a brief risk-of-bias assessment that considers three important aspects relating to each study (detection bias, selection bias and analysis bias).

3. Evidence synthesis: effects of tinnitus on working memory

Perhaps one of the most influential perspectives on working memory has been that of Baddeley and Hitch (1974). They proposed a multi-component model comprising short term memory storage (the phonological loop and the visuospatial sketchpad) and an attention-like system responsible for retrieving information, directing the flow of information through the short term memory system as a whole, controlling action, and planning according to behavioural goals (the central executive). Working memory is typically assessed by tasks that measure storage and processing capacity simultaneously. A simple working memory task is the backwards digit span, requiring the immediate recall of lists of digits in reverse order (e.g. Smith et al., 2013). A complex working memory task is the reading span test by Daneman and Carpenter (1980). This requires the individual to read or listen to a short series of sentences such as ‘the snail crept slowly’, indicate whether each sentence made sense, and then recall the last word of every sentence in the correct serial order. Dual task paradigms are another form of complex task, but these also engage selective and switching attention (see Stuss et al., 1995).

Working memory is a limited capacity resource and this is an important notion for hearing loss and tinnitus. Hearing loss impoverishes phonological input, hence increasing demands on auditory processing and reducing the spare capacity available for conducting other tasks (Rabbitt, 1968, 1990). Given that tinnitus is construed as a consequence of failing to stop attending to an essentially irrelevant signal (Hallam et al., 1984), it also increases demands on auditory processing. Indeed, McKenna (1997) speculated that the presence of tinnitus might also interfere with the capacity of the phonological loop to store auditory verbal information, in the same way as does for hearing loss. Both hearing loss and tinnitus could therefore each separately add to the load on the central executive.

Three included articles directly examined the impact of tinnitus on working memory (Hallam et al., 2004; Rossiter et al., 2006; Stevens et al., 2007). The first (Hallam et al., 2004) sought to test whether people with tinnitus show impaired performance on the cognitive processes described within Baddeley's model of working memory, using four dual-task conditions and one test of delayed serial digit recall. Three groups were recruited; (1) audiology clinic outpatients reporting tinnitus as a primary complaint (N = 43), (2) outpatients of the same clinic reporting hearing loss as a primary complaint (N = 17), and (3) non-clinical controls who reported no noticeable hearing impairment or tinnitus (N = 32). The dual-task condition most closely associated with working memory was the Bakan visual vigilance test with articulatory suppression (repeating ‘Boko’ while performing the test) that was simply intended to occupy the phonological loop but be otherwise irrelevant. The primary task was to monitor for and detect sequences of three consecutive odd or even digits. On this task, the number of correct three-digit identifications was no different across the three groups when age was covaried. Hallam et al. (2004) also presented a delayed serial digit recall task with an irrelevant picture memory task. Analysis considered the position of the recalled digits in the sequence as an independent variable, but the interaction between groups and digit position was not significant when age was covaried. The authors reported a hint of worse performance in recalling the first and second digits for the tinnitus group, but this was based on a post-hoc analysis that was not defined by the initial hypothesis. On the basis of these findings, the authors concluded that whatever the effect of tinnitus on cognitive processing, it is subtle in nature.

In contrast, the second article (Rossiter et al., 2006) concluded that tinnitus *does* interfere with working memory and reduces cognitive capacity needed to perform tasks that require voluntary effortful and strategic control. Two groups were recruited; (1) people experiencing chronic moderate tinnitus (n = 19), and (2) controls reporting no experience of tinnitus in the preceding six months (n = 19). Authors assessed performance based on a dual-task paradigm. The most cognitively demanding condition required participants to detect a rectangle on the computer screen that appeared at variable inter-stimulus intervals from 1 to 9 s, at the same time as performing an irrelevant category naming task. Only on this high-demand dual-task condition was the tinnitus group slower than the control group (by 150 ms), even when covarying for anxiety to account for this confounding factor. The same research team repeated this cognitively demanding version of the dual-task paradigm in a smaller sample of participants (n = 11 in each group) (Stevens et al., 2007). Again, the tinnitus group was significantly slower than the control group, even when covarying for hearing loss, anxiety, and depression. The authors concurred with their previous conclusion that tinnitus depletes cognitive resources.

Rossiter et al. (2006) also reported a working memory task based on the reading span test by Daneman and Carpenter (1980). The tinnitus group recalled significantly fewer final words than controls, even when covarying for anxiety. However, we note that the effect was small (mean recall accuracy was 3.0 and 3.6 in tinnitus and controls respectively).

There is a lack of evidence to support the claim that *severity* of tinnitus negatively impacts on working memory. Stevens et al. (2007) did use individual global scores on the Tinnitus Questionnaire (Hallam, 1996) as a covariate, but this did not have any significant impact on working memory performance. Neither Hallam et al. (2004) nor Rossiter et al. (2006) assessed the impact of tinnitus severity on working memory performance.

On balance, there is mixed support that tinnitus impairs working memory. Further research is warranted.

4. Evidence synthesis: effects of tinnitus on attention

Attention is not a unitary phenomenon. A number of different subtypes have been well characterised in the literature. Perhaps one of the best known is the three component model of Posner and Petersen (1990); alerting, orienting and executive attention. Alerting refers to the readiness to receive information and is measured by the speed of responding to an external cue. Alerting is a rapid (unconscious) process that is not under voluntary control, and hence tends to be short-lived (i.e. less than 150 ms). Orienting attention is defined as the conscious process of selecting task-relevant stimuli and ignoring task-irrelevant stimuli. Orienting is simply another term for selective attention and tends to be longer lived (i.e. more than 150 ms). A review by Banbury et al. (2001) concluded that irrelevant sounds exerted greatest effect on cognitive performance by interrupting selective attention. This is consistent with tinnitus being considered as an irrelevant sound and bothersome tinnitus being a failure to stop attending to an irrelevant sound (c.f. Hallam et al., 1984). Executive attention is responsible for resolving input by engaging, disengaging and switching attention. The model is supported by evidence from experimental psychology, neuropsychology and neuroimaging (Petersen and Posner, 2012; Mirsky et al., 1991; Manly et al., 2001). The Attention Network Test (ANT) (Fan et al., 2002) is a well-validated test developed to assess Posner's framework of attention by providing a measure of the three different components in a single computer-delivered test. Although the test is visual, it is assumed to tap into components of attention that are modality free. In the ANT, participants are required to identify as quickly and as accurately as possible whether the central arrow is pointing leftward or rightward. Components of attention are modulated on each trial by different warning cues and direction of flanker arrows.

A further fundamental component of attention, not assessed by ANT, is sustained attention. Sustained attention relates to the ability to maintain attention over a prolonged period of time and is important for completing repetitive tasks.

4.1. Tinnitus and sustained attention

Perhaps the first studies to address the topic of tinnitus and sustained attention were by McKenna and colleagues (1995; 1999). Both studies used a Letter Cancellation Test as a measure of sustained attention and vigilance. Participants were required to search and cross-out every occurrence of a target letter in an array of letters printed on the page as quickly and as accurately as possible. The 1995 study was conducted in a neuro-otology and audiological rehabilitation clinic with 28 patients reporting tinnitus and 21 controls without. No performance differences were observed across groups. The 1999 study was conducted in the same clinic with 21 patients reporting tinnitus and 17 controls without. There was no difference in reaction time and accuracy between groups, when months since onset of tinnitus symptoms, trait anxiety and hearing loss (worst ear) were added as covariates.

Hallam et al. (2004) included two 4-min tasks to assess sustained attention in tinnitus; the single-task condition comprising the Bakan vigilance test and a five-choice serial reaction time test. The vigilance test required retaining in memory preceding digits over a brief period of time. There were no group differences in the number of correct three-digit identifications. The second task measured self-paced serial responding on a keyboard to the position of a spot appearing at one of five positions over a sequence. Overall accuracy was 88–93%, but there was no difference between groups.

Again, there is a lack of evidence to support the claim that *severity* of tinnitus negatively impacts on sustained attention. None of the studies reviewed evaluated this specific question (Hallam et al., 2004; McKenna et al., 1995; McKenna and Hallam, 1999).

There is no compelling evidence to support the notion that tinnitus impairs sustained attention.

4.2. Tinnitus and alerting attention

The presence of tinnitus may automatically direct attention towards the tinnitus ear, which in turn may compromise the function of the involuntary attention system. In normal controls, tone categorisation performance in one ear is momentarily impaired whenever there is an unpredictable change (a deviant tone) in a task-irrelevant sequence of tones presented to the other ear. This reflects attention capture. Cuny et al. (2004) investigated auditory alerting attention in tinnitus based on the assumption that the maladaptive automatic direction of attention towards the tinnitus ear might promote a ‘tinnitus ear bias’. They predicted a reduced susceptibility to attention capture for targets presented to the tinnitus ear and an enhanced susceptibility in the converse presentation condition. The tinnitus group included 10 people with tinnitus perceived in the right ear and 10 in the left ear. All participants were right–handed males, with normal vision and normal hearing at least up to 2 kHz (the range of the tone stimuli). A categorisation task was performed with two alternative answers (high or low frequency tone) while ignoring standard and deviant tones (oddball sequence) in the other ear. As predicted, accuracy was better when the categorisation tones were presented in the tinnitus ear and the oddball sequence was presented in the non-tinnitus ear (90 correct responses), than vice-versa (86 correct responses). Consistent with the time course of alerting attention, attention capture was most evident when the interval between the to-be-ignored stimulus and the target was 100 ms, was reduced at 150 ms, and absent at 200 ms. Reaction times were not reported for this comparison. Curiously however, when data for the whole tinnitus group (including 10 with bilateral tinnitus) were combined there was also a significantly larger overall reaction time cost when categorisation tones were presented in the right than the left ear. Thus while the first finding is consistent with the proposal that people with tinnitus have more difficulties in redirecting attention to the non-tinnitus ear, the second finding cannot be explained by any attentional hypothesis.

A recent study by Heeren et al. (2014) used the visual ANT to assess the three component model of Posner and Petersen (1990) in tinnitus (n = 20) versus controls (n = 20). The alerting component was calculated by subtracting trials with a non-directional double cue from no cue trials. Accuracy and reaction time did not differ significantly between groups, implying that tinnitus does not interfere with alerting attention.

There is mixed evidence to support the claim that tinnitus *severity* negatively impacts on sustained attention. Cuny et al. (2004) observed an association between alerting attention (measured by individual correct response rate) and scores on the Subjective Tinnitus Severity Scale (Halford and Anderson, 1991). The more severe the tinnitus, the “less efficient” (pp. 299) was the cognitive processing. In contrast to this finding, Heeren et al. (2014) found no significant relationship between alerting attention and duration of tinnitus, nor with the intensity of the coping strategies patients used to reduce the tinnitus as assessed in an unpublished questionnaire (QIPA).

On balance, it is unclear whether tinnitus impairs alerting attention and more studies are needed to answer this question.

4.3. Tinnitus and selective attention

Three studies have directly examined the impact of tinnitus on selective attention (Hallam et al., 2004; Stevens et al., 2007; Heeren et al., 2014).

Hallam et al. (2004) used a variable fore-period reaction time task. In this single-task condition, the participant was instructed to wait for and respond to a visual stimulus that appeared between 1 and 5 s following a warning cue (audible beep). The task was rather repetitive and lasted 4 min; perhaps therefore also engaging sustained attention. Mean reaction times observed in their tinnitus group (396 s) were significantly slower than in their non-clinical control group (342 s), even when age was covaried, but did not however differ from their hearing-impaired group (376 s).

The Stroop test involves saying out loud the ink colour of a printed set of words that are names of the colours themselves, when some of those colour names are congruent and some incongruent. It is usually administered as a test of the central executive because incongruent trials require the participant to suppress the more salient response which is to name the colour word. The classic Stroop effect is defined as the difference in naming reaction times between congruent and incongruent colour-word trials. However, Stevens et al. (2007) purported to assess selective attention in tinnitus (n = 11) by using the Stroop test but averaging together both congruent and incongruent trials. For the “say colour" conditions, the reaction time for the tinnitus group was slower (1559 ms) than for a control group (912 ms, n = 11) that had no history of tinnitus in the preceding six months. This finding was maintained when hearing loss, depression and anxiety were accounted as covariates. The authors interpreted these findings in support of a tinnitus-related deficit in selective attention.

Heeren et al. (2014) examined selective attention using the visual ANT. Here, the selective attention component was examined by changes in accuracy and reaction time that accompanied warning cues indicating whether the central arrow target would appear on the left or the right of the screen ('orienting'). Cues were either valid or invalid, with selective attention reflecting the difference between the two. The results showed no significant difference between groups on either dependent variable, implying that tinnitus does not interfere with selective attention.

The impact of tinnitus severity on selective attention performance was assessed in two studies (Heeren et al., 2014; Stevens et al., 2007), but no significant relationship was found. Hallam et al. (2004) did not assess this association.

Findings provide mixed support for the notion that tinnitus impairs selective attention, although the balance of evidence is against this claim.

4.4. Tinnitus and executive attention

Executive attention is responsible for resolving input by engaging, disengaging, and switching attention. It is involved in working memory processing, and so the two theoretical constructs interrelate. The colour-word Stroop task is a well-recognised neuropsychological measure of executive functioning (e.g. Smith et al., 2013). Incongruent trials reliably lead to performance costs in both reaction times and accuracy (the 'classical Stroop effect'), reflecting the need to inhibit the irrelevant stimulus feature and its corresponding inappropriate response. Although the data acquired by Stevens et al. (2007) could have been used to examine central executive processing by comparing congruent and incongruent trials on the colour-word Stroop task, only two studies have actually done so (Andersson et al., 2000; Jackson et al., 2014). Andersson et al. (2000) compared people with a tinnitus problem rated as grade II or III (according to Klockhoff and Lindblom, 1967) (n = 23) and controls reporting no tinnitus (n = 23). Although people with tinnitus responded more slowly than controls, there was no difference between groups in terms of the classical Stroop effect.

Jackson et al. (2014) administered the colour-word Stroop to two groups of participants, broadly matched on age. The tinnitus group was 33 participants with low to moderate tinnitus distress according to the Subjective Tinnitus Severity Scale, reporting no ongoing treatment or therapy for their tinnitus. The control group was 33 participants scoring zero on the tinnitus severity questionnaire. Reaction time analysis again revealed that people with tinnitus responded more slowly than controls, but there was no difference between groups in terms of the classical Stroop effect.

Heeren et al. (2014) used the visual ANT in which the executive attention component was examined by differences in the reaction time for congruent trials (where the flanker arrows and the central arrow all point in the same direction) and incongruent trials (where they point in the opposite direction). The tinnitus group (n = 20) had significantly slower reaction times than the control group (n = 20), even when gender, age, education, anxiety and depression were covaried. This index of executive control deficit averaged about 38 ms across cue types. The authors concluded that tinnitus interferes with the executive control of attention.

There is preliminary evidence supporting the claim that severity of self-reported tinnitus symptoms negatively impacts on executive attention. For Jackson et al. (2014), a post-hoc analysis indicated a significant positive correlation between scores on the Subjective Tinnitus Severity Scale and reaction time (as well as error rate) on the incongruent colour-word Stroop trials. Meanwhile, Heeren et al. (2014) also reported that the degree of the executive control impairment was significantly correlated with duration of tinnitus, as well as with the intensity of the coping strategies they used to reduce the tinnitus as assessed in an unpublished questionnaire (QIPA). The impact of tinnitus severity on Stroop performance was not assessed by Andersson et al. (2000).

5. Evidence synthesis: cognitive performance in those reporting concentration or memory difficulties

In this section, we gather evidence for the link between impaired cognitive performance and those reporting everyday concentration or memory difficulties.

Working memory and attention have been studied largely in isolation from other cognitive processes, although clearly they operate as an interdependent system with the related cognitive processes of perception and memory. The more successful we become at examining part of the cognitive system in isolation, the less our data are likely to tell us about cognition in everyday life. If self-reported difficulties in mental concentration are indeed attributable to a negative effect of tinnitus on cognitive performance, then it is important for such a link to be supported by empirical evidence. People with a mild tinnitus severity may not experience symptoms that disrupt daily life and so those studies recruiting a restricted sample of participants may be unable to address this question (e.g. Rossiter et al., 2006). Nevertheless, of the nine included studies, four did examine the association with concentration or memory difficulties. All four studies evaluated self-reported concentration difficulties using the Cognitive Failures Questionnaire (CFQ, Broadbent et al., 1982). Evidence is somewhat mixed. Two studies report group differences on the CFQ, and two do not. McKenna et al. (1995) reported higher CFQ scores in the tinnitus group than in controls (mean = 42 and 34, respectively) and draw the conclusion that the tinnitus group may have "difficulty in coping cognitively" pp. 594. Similarly, of those in the tinnitus group recruited by Hallam et al. (2004), 16 out of 26 responded yes to the question 'Do you think tinnitus makes you absent-minded or forgetful or inclined to lose concentration?'. However, in their later study (McKenna and Hallam, 1999), the authors were surprised to report no group differences in mean CFQ (tinnitus and controls, mean = 48 and 42, respectively). This null finding was repeated by Rossiter et al. (2006) who also observed that tinnitus and control groups did not differ in their results on the CFQ (mean CFQ = 46 and 41, respectively).

Only Hallam et al. (2004) conducted a correlation between cognitive performance and CFQ scores. They found that CFQ was also correlated with performance on the dual task version of the delayed serial recall of digits (a test of working memory), albeit with a small correlation value. Although these preliminary findings are positive, whether they are specific to tinnitus is uncertain because a high proportion of people in Hallam's hearing-impaired group also reported cognitive difficulties (tinnitus mean CFQ = 45, hearing impaired mean CFQ = 37).

Whether a link between performance-based and patient-reported measures exists cannot be answered by the present data. This question warrants further investigation and so we recommend that future studies collect both types of data.

6. Risk of bias assessment

Risk of bias (detection, selection, analysis) was examined using a checklist to make a judgement about the extent to which results of the included studies should be believed (Higgins and Green, 2011: pp. 189). For each feature of selection bias, a judgement was made independently by two authors (i.e. low risk, high risk, unclear risk) with the third serving as arbitrator. Supporting evidence for that judgement is also reported.

6.1. Detection bias

Many cognitive or neuropsychological tests have been established as validated measures designed to place greater information processing demands on one component of cognition than on another. Illustrative examples of the more common standardised tests are given in previous sections of the review (Sections 4 and 5). Detection bias includes any use of poorly validated or 'faulty' measurement techniques (Higgins and Altman, 2011). Table 1 provides a summary of the original sources for the cognitive tests that were selected in each of the nine studies.

Unless the test is an 'off the shelf' or commercially available set of materials, it is not straightforward for us to make a reasonable judgement about how validated each of the different tests is. For example, there can always be differences in the way that individual authors set up and implemented the test. However, our study appraisal revealed that at least one group of authors (Rossiter et al., 2006; Stevens et al., 2007) created their own 'non-validated' test, while another modified an existing test (Cuny et al., 2004). Hallam et al. (2004) cite source articles that appear to be only indirectly related to the Bakan visual vigilance and five choice serial reaction time tests. These four studies are therefore more likely to present a high risk of detection bias.

6.2. Selection bias

Any interpretation of a *direct* link between tinnitus and specific cognitive components can be distorted by the presence of another variable which gives rise to differences between baseline characteristics of the groups (e.g. Hallam et al., 2004). These are confounding factors associated with a *selection bias*. Age, gender and hearing loss are potential confounds already highlighted by tinnitus researchers as important for group matching in other research contexts (e.g. Lanting et al., 2009). Indeed, in one of the studies reviewed here, Andersson et al. (2000) stated that "Yet another explanation [for the generally worse performance by the tinnitus group] is that the increased latencies are caused by hearing impairment. This alternative cannot be excluded, and future studies should benefit from the inclusion of a comparison group matched for degree of hearing loss." pp. 1172. Hallam et al. (2004) also acknowledged that hearing impairment, general emotional distress and general intellectual ability could all contribute to poor concentration and cognitive difficulties in people with tinnitus. There is empirical evidence that poor psychological well-being impairs all of the main three components of working memory (Christopher and MacDonald, 2005), particularly the central executive component of working memory (Channon et al., 1993; Eysenck et al., 2005; Hartlage et al., 1993). For all nine records, we made a judgement about the level of risk of selection bias (high, low or unclear) with supporting evidence in the form of quotes taken directly from the corresponding article (Table 2 columns 2 and 3, respectively). Risk of bias assessment was based purely on the recruitment

Table 1
Original sources of cognitive tests used to assess the impact of tinnitus on working memory and attention, relating to detection bias.

	Provenance of the test
Working memory	
Dual-task: Bakan visual vigilance test: (Hallam et al., 2004)	Reference: Smith AP, Miles C. 1985. The combined effects of noise and night work on human function. In: Brogan D (ed.) Contemporary Ergonomics. London: Taylor & Francis, pp. 33–41.
Dual-task: Delayed serial digit recall task (Hallam et al., 2004)	Reference: Smith AP. 1983. The effects of noise and memory load on a running memory task. Br J Psychol, 74, 439–45.
Dual task: detect a rectangle and perform an irrelevant category naming task (Rossiter et al., 2006; Stevens et al., 2007)	Created by authors.
Reading Span Test (Rossiter et al., 2006)	Reference: Daneman M, Carpenter PA. 1980. Individual differences in working memory and reading. Journal of Verbal Learning and Verbal Behaviour 19, 450–66.
Sustained attention	
Letter Cancellation Test (McKenna and Hallam, 1999; McKenna et al., 1995)	Reference: Lezak M. 1983. Neuropsychological assessment. Oxford: Oxford University Press.
Single-task: Bakan visual vigilance test (Hallam et al., 2004)	Reference: Smith AP, Miles C. 1985. The combined effects of noise and night work on human function. In: Brogan D (ed.) Contemporary Ergonomics. London: Taylor & Francis, pp. 33–41.
Five-choice serial reaction time test (Hallam et al., 2004)	Reference: Smith A, Tyrell DAJ, Al-Nakib, W, Coyle KB, Donovan CB et al., 1987. Effects of experimentally induced respiratory virus infections on psychomotor performance. Neuropsychobiology 18, 144–8.
Alerting attention	
Categorisation while ignoring standard and deviant tones (oddball sequence) (Cuny et al., 2004)	Derived from: Schröger E, 1996. A neural mechanism for involuntary attention shifts to changes in auditory stimulation. J Cogn Neurosci 8, 527–39.
Attention Network Test (Heeren et al. (2014)	Reference: Fan J, McCandliss BD, Sommer T, Raz A, Posner MI. 2002. Testing the efficiency and independence of attentional networks. J Cogn Neurosci 14, 340–7.
Selective attention	
Variable fore-period reaction time task (Hallam et al., 2004)	Smith AP, Tyrell DAJ, Coyle KB, Willman JS. 1987. Selective effects of minor illnesses on human performance. Br J Psychol, 78, 183–8.
Colour-word Stroop task (Stevens et al. (2007))	Reference: none
Attention Network Test (Heeren et al. (2014)	Reference: Fan J, McCandliss BD, Sommer T, Raz A, Posner MI. 2002. Testing the efficiency and independence of attentional networks. J Cogn Neurosci 14, 340–7.
Executive attention	
Colour-word Stroop task (Andersson et al., 2000)	Reference: MacLeod CM. 1991. Half a century of research on the Stroop effect: an integrative review. Psychological Bulletin 109, 163–203.
Colour-word Stroop task (Jackson et al., 2014)	Stroop 1935 referenced in: Küper K, Heil M. 2012. Attentional focus manipulations affect naming latencies of neutral but not of incongruent Stroop trials. Swiss J Psychol 7, 93–100.
Attention Network Test (Heeren et al. (2014)	Reference: Fan J, McCandliss BD, Sommer T, Raz A, Posner MI. 2002. Testing the efficiency and independence of attentional networks. J Cogn Neurosci 14, 340–7.

Table 2
Study appraisal for evidence of selection bias. Unclear risk denotes insufficient information about the allocation process to permit judgement of 'Low risk' or 'High risk'. BDI = Beck Depression Inventory, CS = control subjects, HADS = Hospital Anxiety and Depression Scale, HADS-A = anxiety subscale, HADS-D = depression subscale, HFAHL = High frequency average hearing level, NART = National Adult Reading Test, MMSE = Mini Mental State Exam STAI = Spielberger Stait Trait Anxiety Inventory, STAIS-S = Spielberger Stait Trait Anxiety Inventory-State version, TS = tinnitus subjects, and WAIS-R = Weschler Adult Intelligence Scale-Revised.

	Review authors' judgement	Support for judgement	*Accounting for any potential selection bias in analysis*
Andersson et al. 2000			
Selection bias: age	Low risk	Quote: "…a group of tinnitus patients and an age- and gender-matched control group…"	*Not accounted*
Selection bias: gender	Low risk	Quote: "…a group of tinnitus patients and an age- and gender-matched control group…"	*Not accounted*
Selection bias: hearing loss	High risk	Quote: "In the tinnitus group, 20 participants had a hearing impairment,…" and "The control participants … All reported normal hearing…" Comment: Only considered after group allocation.	*Not accounted*
Selection bias: General emotional distress	High risk	Quote: "Unpaired t tests revealed significant differences in the BDI, the SAIS-S,…"	*Quote: "to investigate whether scores on the BDI or on the STAI-S had affected the results on the Stroop test, results were correlated. No significant correlation was found regarding latencies and interference…"*
Selection bias: Intellectual ability	Low risk	Quote: [unpaired t-tests did not reveal any significant difference] "on the WAIS-R." Comment: Only considered after group allocation.	*Not accounted*
Cuny et al. 2004			
Selection bias: age	Low risk	Comment: Table 1 reports mean (and standard deviation) after group allocation. Right tinnitus group = 43(12), Left tinnitus group = 43(11), Bilateral tinnitus group = 44(13).	*Not accounted*
Selection bias: gender	Unclear risk	Comment: Not reported.	*Not accounted*
Selection bias: hearing loss	Low risk	Quote: "…all subjects … had normal hearing at least up to 2000 Hz (0 ± 10 dB HL)."	*Not accounted*
Selection bias: General emotional distress	Unclear risk	Comment: Not reported.	*Not accounted*
Selection bias: Intellectual ability	Unclear risk	Comment: Not reported.	*Not accounted*
Hallam et al. 2004			
Selection bias: age	High risk	Quote: NON-CLINICAL CONTROL GROUP were "matched as closely as possible for age…" Comment: Age differences across the patient groups were observed. Table 1 reports mean (and standard deviation) after group allocation. Tinnitus group = 49(12), Acquired hearing loss = 51(9), Normal control = 41(12). F[2,89] = 5.61, p = 0.005	*BAKAN VISUAL VIGILANCE (dual task) Quote: "the difference between groups becomes non-significant when age is covaried (F[2,87] = 2.67, p < 0.10)." DELAYED SERIAL RECALL OF DIGITS Quote: "the level of significance is reduced when age is covaried (F[2,86] = 2.81, p < 0.07)." BAKAN VISUAL VIGILANCE (single task) Quote: "the difference between groups becomes non-significant when age is covaried (F[2,87] = 2.67, p < 0.10)." VARIABLE FORE-PERIOD REACTION TIME (single task) Quote: The group effect remains significant when age is covaried (F[2,87] = 4.47, p < 0.02).*
Selection bias: gender	High risk	Comment: Table 1 reports descriptive data after group allocation for M:F. TS = 27:16, Acquired hearing loss = 7:10, Normal control = 16:16.	*Not accounted*
Selection bias: hearing loss	High risk	Quote: "TINNITUS GROUP … whose main complaint was tinnitus … HEARING IMPAIRMENT GROUP … whose main complaint was hearing impairment … NON-CLINICAL CONTROL GROUP … reported no noticeable hearing impairment or tinnitus."	*Not accounted*
Selection bias: General emotional distress	High risk	Comment: Table 1 reports mean (and standard deviation) for State and Trait Anxiety and Mood after group allocation. For Trait Anxiety, TS = 42(11), Acquired hearing loss = 35(10), Normal control = 34(6). F[2,89] = 6.59, p = 0.002	*Not accounted*
Selection bias: Intellectual ability	High risk	Comment: Table 1 reports mean (and standard deviation) for NART after group allocation. TS = 13(8), Acquired hearing loss = 19(12), Normal control = 11(9). F[2,89] = 4.51, p = 0.02	*Not accounted*
Heeren et al. 2014			
Selection bias: age	Low risk	Quote: "Patients were matched for age …"	*Quote: "Analyses of covariance were performed to test the influence of potential biasing variables (i.e., … age…) on RTs and accuracy scores in ANT".*
Selection bias: gender	Low risk	Quote: "Patients were matched for … gender …"	*Quote: " Analyses of covariance were performed to test the influence of potential biasing variables (i.e., … gender…) on RTs and accuracy scores in ANT".*
Selection bias: hearing loss	High risk	Quote: "Eligible participants … had sufficient hearing abilities to follow the instructions." Comment: Probably not quantified.	*Not accounted*
	Low risk		

(*continued on next page*)

Table 2 (*continued*)

	Review authors' judgement	Support for judgement	*Accounting for any potential selection bias in analysis*
Selection bias: General emotional distress		Quote: "As shown in Table 1, TS and CS did not significantly differ in terms of … depression [t(38) = 0.50, p = 0.62], and trait anxiety [t(58) = 0.10, p = 0.93] …" Comment: Table 1 reports mean (and standard deviation). Depression, TS = 6(9), CS = 8(9) and anxiety, TS = 24(9), CS = 24(9).	*Quote: "Analyses of covariance were performed to test the influence of potential biasing variables (i.e., … depression, anxiety…) on RTs and accuracy scores in ANT".*
Selection bias: Intellectual ability	Unclear risk	Comment: Reported educational level and MMSE screen for major cognitive impairment only.	*Quote: "Analyses of covariance were performed to test the influence of potential biasing variables (i.e., … MMSE…) on RTs and accuracy scores in ANT".*
Jackson et al. 2014			
Selection bias: age	Low risk	Quote: "In order to neutralize possible confounding effects of age, attempts were also made to match both groups along this variable."	*Not accounted*
Selection bias: gender	Low risk	Comment: Authors report descriptive data after group allocation for M:F. TS = 17:16, CS = 16:17.	*Not accounted*
Selection bias: hearing loss	Unclear risk	Comment: All participants reported they were comfortable conversing in quiet surroundings.	*Not accounted*
Selection bias: General emotional distress	Low risk	Quote: "Scores for both groups were thus in the normal range." Comment: Authors report descriptive data after group allocation for HADS. HADS-D, TS = 4(3), CS = 3(2). HADS-A, TS = 7(4), CS = 6(2).	*Quote: "There were no significant correlations between … performance measures and HADS-A.*
Selection bias: Intellectual ability	High risk	Comment: Not reported.	*Not accounted*
McKenna et al. 1995			
Selection bias: age	Low risk	Quotes: "The control group was drawn from patients complaining of acquired hearing loss and without tinnitus." … who were attending the same clinics." "There was no significant difference between the ages of the groups." Comment: Analysis conducted after group allocation. Table 1 reports mean (and standard deviation). TS = 42(10), CS = 39(11), p = 0.26.	*Not accounted*
Selection bias: gender	High risk	Quote: "The tinnitus group consisted of 17 male and 11 female subjects. The control group consisted of 11 male and 10 female subjects."	*Not accounted*
Selection bias: hearing loss	High risk	Quote: "The mean hearing loss of the control group was significantly greater than that of the tinnitus group." Comment: Table 2 reports mean (and standard deviation) hearing for best ear. Tinnitus group = 28(17), Control group = 42(21) p = 0.04 (same pattern for worse ear)	*Not accounted*
Selection bias: General emotional distress	High risk	Quote: "The tinnitus group tended to obtain higher scores on the STAI; this difference was significant for only Trait Anxiety." Comment: Table 3 reports mean (and standard deviation) for Trait Anxiety. Tinnitus group = 43(12), Control group = 35(8), p = 0.01. Depressive symptoms not reported.	*Quote: "When the influence of Trait anxiety was taken into account statistically, the overall picture of poorer performance among tinnitus patients remained."*
Selection bias: Intellectual ability	Low risk	Quote: "The two groups were very closely matched in terms of general intellectual status." Comment: Table 3 reports mean (and standard deviation) for NART IQ Equivalent. TS = 112(7), CS = 112(7), p = 0.90.	*Not accounted*
McKenna and Hallam, 1999			
Selection bias: age	Low risk	Quote: "The control group was drawn from patients attending the same clinics … in order to minimise the differences … between groups." Comment: TS = 45(11), CS = 38(10). The difference in mean ages was not significant.	*Not accounted*
Selection bias: gender	Unclear risk	Comment: Not reported.	*Not accounted*
Selection bias: hearing loss	High risk	Comment: Analysis conducted after group allocation. Table 1 reports mean (and standard deviation) hearing for best ear. TS = 25(22), CS = 46(31). T(33) −2.26, p < 0.05 (same pattern for worse ear)	*Quote: "When hearing loss in the better ear was used as a covariate … difference in scores on the … Letter Cancellation test was non-significant." (same pattern for the worse ear)*
Selection bias: General emotional distress	High risk	Quote: "The Tinnitus group obtained significantly higher Trait anxiety scores t = 2.74; df = 37,p < 0.01) on the STAI." Comment: Depressive symptoms not reported.	*Quote: "The differences … were non-significant when Trait anxiety was used as a co-variate."*
Selection bias: Intellectual ability	Low risk	Comment: Table 2 reports mean (and standard deviation) for NART. TS = 107(10), CS = 111(9). t = 2−1.03, p = *n.s.*)	*Not accounted*
Rossiter et al., 2006			
Selection bias: age	Low risk	Quote: "… the control group … matched to individuals from the experimental group according to age …"	*Not accounted*
Selection bias: gender	High risk	Comment: Author reports descriptive data after group allocation for M:F. TS = 16:3, CS = 13:6.	*Not accounted*
Selection bias: hearing loss	High risk	Quote: "We did not measure participants' hearing threshold levels or try to match the … groups on this variable."	*Not accounted*
Selection bias: General	High risk	Quote: "The mean State Anxiety score for the tinnitus group was 37(9) and for the control group was 31(6). Mean Trait Anxiety score	*Quote: "The ANCOVA retained a significant effect of group (tinnitus-nontinnitus) and revealed no effect of state anxiety on reading span,*

Table 2 (*continued*)

	Review authors' judgement	Support for judgement	*Accounting for any potential selection bias in analysis*
emotional distress		for the tinnitus a group was 39(12) and for the control group was 32(5)"	*F(1,35) = 0.30, p > 0.05."* *[for the dual-task] "An ANCOVA, with state anxiety as a covariate, revealed no significant effect of anxiety for task condition or participant group."*
Selection bias: Intellectual ability	Low risk	Quote: "…the control group … matched to individuals from the experimental group according to … score on the NART"	*Not accounted*
Stevens et al., 2007			
Selection bias: age	Low risk	Quote: "Individuals selected for the control group were matched to individuals from the experimental group according to age, verbal IQ …" Comment: The control group was selected after the experimental group.	*Not accounted*
Selection bias: gender	High risk	Quote: "The experimental group consisted of… seven males and four females… the [control] group consisted of five male and six female adults."	*Not accounted*
Selection bias: hearing loss	High risk	Quote: "The overall mean for the tinnitus group was 37.24 dB HFAHL … for the control group was 27.69 dBL …"	*Quote: "…the results are not explained by co-variation with … …high frequency average hearing level."*
Selection bias: General emotional distress	High risk	Quote: The mean state anxiety score for the tinnitus group was 46(12)… and for the control group 31(11). Mean trait anxiety score for the tinnitus group was 48(12) and for the control group 35(13) … The mean BDI score for the tinnitus group was 17(10), and for the control group 9(12)."	*Quote: "…the results are not explained by co-variation with anxiety, depression … ."*
Selection bias: Intellectual ability	Low risk	Quote: "Individuals selected for the control group were matched to individuals from the experimental group according to … verbal IQ…"	*Not accounted*

criteria and descriptive statistics of the sample characteristics. To some extent, bias can be mitigated retrospectively by accounting for observed baseline differences in the primary analysis. Hence, we also noted instances where the addition of covariates has or has not been implemented by the authors (Table 2, column 4).

Studies reviewed here control for confounding factors to varying degrees of success. We recommend careful consideration of future study design to avoid selection bias.

6.3. *Analysis bias*

No cognitive construct can be directly measured, but must be inferred by examining performance on carefully designed tests that place greater demand on a specific component of cognition. Shipstead et al. (2012) noted that the performance score on a single test probably fails to isolate the cognitive component of interest because it potentially reflects the contribution of other processes such as decision making and speed of motor responses (see also Kane et al., 2004; Alloway et al., 2006). Hence, studies that draw inferences from a single measure on one task carry a higher risk of *analysis bias*, than those which pool across multiple independent measures.

Analysis bias is the final form of bias that is addressed in our review. We considered all nine articles with respect to whether the authors' interpretations of findings is based on analysis that pools across multiple independent measures of a particular latent construct (such as working memory). According to our classification of tests, Hallam et al. (2004) and Rossiter et al. (2006) both administered several tests of working memory, while Hallam et al. (2004) administered several tests of sustained attention. In such cases analyses were always conducted separately on individual tests, never pooled together. The other seven records delivered only one test to assess each cognitive component. Hence, according to our evaluation criteria, all of the studies carry a high risk of analysis bias. Based on this assertion, we strongly recommended using multiple validated measures to assess any single underlying construct.

7. Concluding remarks

Our review findings highlight a need for further research to answer the question about the impact of tinnitus on cognition. From the risk of bias assessment, we have made a number of recommendations for researchers to consider in the design and analysis of such future studies. We bring together all of this information to propose a unified theoretical model of tinnitus and cognition (Fig. 2) that stands as a hypothesis for testing. The model includes the five cognitive components of interest and the important potential confounding factors reviewed here. All theoretical constructs are shown in Fig. 2 by the grey ovals to denote latent variables. Note that the confounding effect of age is important but can be addressed by using age-scaled scores as the measured variables. The interrelationships between the latent variables currently reflect our 'best informed guess' about how the different components of the model affect one another. Experimental studies that seek to manipulate the influence of tinnitus on working memory and/or attention (e.g. Hesser et al., 2013) or clinical trials that examine the consequences for cognition of a therapeutic intervention for tinnitus could also be informative for evaluating the causal claims.

Crucially, to minimise analysis bias, one would propose that each latent variable is assessed using multiple tests in order to 'extract' the common underlying aspect of performance variability that can be explained by the theoretical construct in question. Each measured variable is represented in Fig. 2 by a rectangle. Once the number of measured variables is decided, then it is possible to calculate the sample size estimate using known statistical approaches. MacCallum et al. (1996) describes a method for directly estimating power for a given effect size, sample size and degrees of freedom. We can then use structural equation modelling to ascertain how well the data are explained by the interrelationships

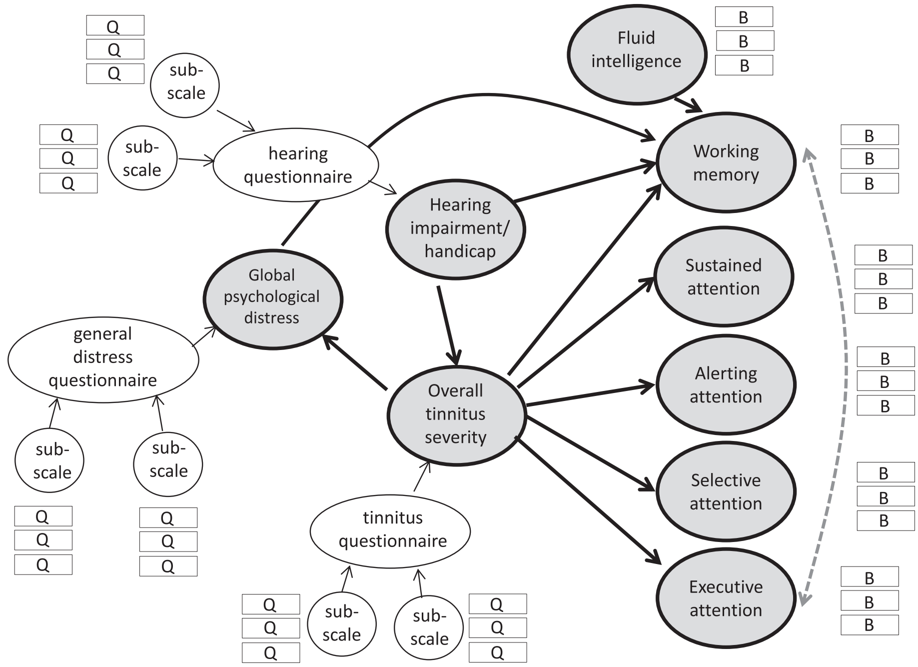

Fig. 2. Putative model describing the consequences of tinnitus on working memory and attention. Overall tinnitus drives some of the variability in cognitive performance, as captured by the higher-order latent variables (working memory, sustained attention, alerting attention, selective attention and executive attention). Potential confounding factors include intelligence, well-being, and hearing loss. All these higher-order latent variables are represented by grey ovals. Some of the higher-order latent constructs are in turn defined by lower-order latent constructs (white ovals) which represent questionnaire instruments. The white rectangles denote the observed (measurement) variables that are associated with each instrument (questionnaire item 'Q' or behavioural test 'B'). Connections indicate hypothesised causal relationships. For example, the arrow pointing towards working memory from tinnitus severity indicates that tinnitus severity predicts working memory performance. The least certain connection is shown by the dotted grey line. This may depend on the choice of measurement variables.

between tinnitus and the various explanatory components shown in the model. Of course, another important feature of future work should be for researchers to directly address whether self-reported concentration difficulties, cognitive failures and mishaps are related to theoretical constructs of cognition.

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