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The Role of Working Memory Capacity in Auditory Distraction

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“No breakthrough, but at least a new way of thinking”

“Technicalities”

- two senior colleagues’ evaluations of some ideas presented in this thesis.
Abstract

The basis of individual differences in susceptibility to auditory distraction has been a research field largely ignored. The current work presents four studies demonstrating that individual differences in working memory capacity (WMC) are related to the magnitude of auditory distraction. The first three reports showed that high WMC attenuates the effects of speech and aircraft noise on reading comprehension and prose memory. The fourth report showed that high WMC attenuates the power of unexpected sound stimulation to capture our attention, but not the interference from changing-state sound streams to seriation processes. Furthermore, the first and the second report showed that the capacity to exclude new, potentially relevant but ultimately irrelevant, materials from memory underlies the relationship between WMC and the effects of speech on reading comprehension/prose memory. Based on these results, a new perspective of WMC called the “sub-process view” was developed, according to which WMC is a compound of functionally distinct sub-processes: some of which are related to auditory distraction. Ten years ago it was not at all clear if cognitive-control processes play a role in auditory distraction, but the studies reported in this thesis strongly suggest that cognitive-control—as reflected in WMC—constitutes a fundamental basis of individual differences in susceptibility to auditory distraction.
List of publications


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Introduction

Try to read this while people are talking in the background. Are you distracted? To some of us, it is nearly impossible to understand what we read in those situations, whereas others are roughly unaffected by noise in their surroundings. What is the basis of those individual differences? The present thesis is concerned with this question.

Short-term serial recall is probably the most common task in laboratory research on auditory distraction. In this task, participants view short lists of individually and sequentially presented items (e.g., eight unrelated words) and thereafter they recall the items in order of presentation (serial recall). Some trials are performed in silence whereas others are performed against a background of sound and when sound is present recall is usually reduced. There are two prerequisites for this irrelevant sound effect. First, for disruption to take place, the individual elements in the sound stream must be perceptually discrete. For instance, the sound sequence “k l m v q c” is more disruptive to serial recall than the sound sequence “r r r r r r r”. This difference in disruptive power amongst changing-state sound sequences and steady-state sound sequences is known as the changing-state effect (Jones & Macken, 1993). Second, changing-state sound sequences are more disruptive insofar the task requires order processing. If the task does not require order-processing, as when the participants are requested to recall the items in free order instead of serial order, changing-state sound sequences are no more disruptive than steady-state sounds (Jones & Macken, 1993). Based on these findings, it has been suggested that the changing-state effect is a product of interference between similar order processes (for a review, see Macken, Tremblay, Alford, & Jones, 1999). That is, the automatic processing of the order between successive and perceptually discrete sound elements is in conflict with the deliberate processing of the order between individual memory items in the serial recall task. This interference-by-process account has received much support during the last two decades. For instance, changing-state sound
sequences disrupt serial order memory, not item memory, even when the task-instructions are to recall the items in free order (Beaman & Jones, 1998). Moreover, irrelevant sound disrupts sequence learning in paradigms other than the typical serial recall paradigm (Farley, Neath, Allbritton, & Surprenant, 2007) whereas tasks that require little or no serial order processing are largely unaffected by irrelevant sound (Beaman & Jones, 1997). Hence, the magnitude of disruption caused by changing-state sound sequences seems to be a function of the degree of serial order processing required by the primary task, consistent with an interference-by-process account of the irrelevant sound effect.

The basis of individual differences in susceptibility to the irrelevant sound/changing-state effect initially proved difficult to understand. One possibility that first attracted attention from researchers was differences in short-term memory capacity (i.e., performance on a simple-span task). However, the attempts to find a relationship between simple-span performance and the magnitude of the effect failed, demonstrating correlations close to zero (Ellermeier & Zimmer, 1997; Neath, Farley, & Surprenant, 2003). This lack of a correlation may have been the result of inadequate measures of “capacity”. Particularly, a complex-span task may be more suitable than a simple-span task. In a complex-span task, the participants switch between a distractor activity and encoding to-be-recalled words. For example, in the “operation span” (OSPAN) task developed by Turner and Engle (1989), the participants view sets of operation-word strings (e.g., “Is \(4 \times 3 + 5 = 17\)? CACTUS”) with the task to respond “yes” or “no” to the operation and to remember the word for later recall. After responding to a set of those operation-word strings, the participants are probed to recall the words in order of presentation. Complex-span tasks have been used to measure what is called working memory capacity (WMC) in contrast to short-term memory capacity as traditionally measured with tasks that do not have a distractor activity sandwiched in-between presentation of the to-be-recalled words. Individual differences in WMC are extremely
successful in predicting performance across a wide range of domains (for reviews, see Engle, 2002; Jarrold & Towsø, 2006; Lustig, Hasher, & Zacks, 2008; Unsworth & Engle, 2007). For instance, WMC predict performance on four tasks widely believed to require cognitive control: the anti-saccade task (Kane, Bleckley, Conway, & Engle, 2001; Unsworth, Schrock, & Engle, 2004), Eriksen’s flanker task (Heitz & Engle, 2007), the attention network test (Redick & Engle, 2006) and the colour-word Stroop task (Kane & Engle, 2003). Consider Eriksen’s flanker task as an example. Heitz and Engle asked participants to perform the flanker task while steadily increasing the required response speed during the experimental session. In this task, participants should respond as quickly as possible to a central letter (e.g., “S” or “H”) surrounded by to-be-ignored flankers (e.g., “HHSHH” or “SSHSS”). Heitz and Engel’s investigation revealed that high-WMC individuals reach their maximum level of performance faster than low-WMC individuals, which indicates that high-WMC individuals constrain their attentional scoop to task-relevant stimuli (i.e., the central letter) faster than low-WMC individuals do. Findings such as these have led some authors to argue that WMC reflects individual differences in an all-purpose, domain-general and limited pool of cognitive-control resources that can be used to inhibit irrelevant information (Lustig, May, & Hasher, 2001), constrain attention to the primary task (Kane et al., 2001; Heitz & Engle, 2007) and to maintain items in primary memory in the presence of distraction (e.g., Cowan, 2005; Unsworth & Engle, 2007). Because of this, one would expect people who perform well on complex-span tasks to be less susceptible to the changing-state effect. However, several authors have tried, but failed, to find this relationship (Beaman, 2004; Elliott & Cowan, 2005; but see Elliott, Barrilleaux, & Cowan, 2006). Taken together, the weight of evidence indicates that the capacity of working memory is not the basis of individual differences in susceptibility to the changing-state effect.
If WMC is not the basis of those individual differences, then what is? In a recent investigation, Macken, Phelps and Jones (2009) asked participants to listen to pairs of sound-patterns and requested them to judge whether or not the two patterns in each pair were the same. The authors argued that the pattern-matching task measures the capacity to automatically process order information in sound sequences. Later, the participants performed a serial recall task which provided a person-specific measure of the magnitude of the changing-state effect. Consistent with the authors’ expectations, the participants who performed well on the pattern-matching task were the ones most susceptible to the changing-state effect. Based on these findings, the authors concluded that the magnitude of the changing-state effect is a function of the efficiency by which people involuntarily process the order between perceptually discrete sound events. This interpretation is consistent with the idea that the changing-state effect is caused by interference between similar order processes (Macken et al., 1999). From this perspective, the changing-state effect is a consequence of perceptual processing of the sound rather than cognitive processing (see also Macken, Tremblay, Houghton, Nicholls, & Jones, 2003). Since WMC seems to reflect cognitive control capabilities, this may explain why high WMC cannot attenuate or overrule the changing-state effect. The assumption that WMC is unrelated to the changing-state effect receives yet further support from developmental research. Specifically, the magnitude of the changing-state effect appears to be equal amongst younger and older adults (Beaman, 2005; Bell & Buchner, 2007) even though it is well-known that older adults have lower WMC than young adults (e.g., Salthouse & Babcock, 1991). Altogether, the current literature suggests that the changing-state effect is a function of a conflict between similar order processes, not a function of attentional resources or cognitive-control capabilities.

No role for working memory capacity in auditory distraction?
Could individual differences in WMC be related to some auditory distraction phenomena other than the changing-state effect? To answer this question, consider the role of phonology and semanticity in cross-modal disruption by speech. The magnitude of the irrelevant sound effect seems unaffected by the phonological similarity between the irrelevant sound and the to-be-recalled materials (LeCompte & Shaibe, 1997; Marsh, Vachon, & Jones, 2008b), despite initial beliefs to the contrary (Salamé & Baddeley, 1982). Similarly, the semantic meaning of the sound seems to add nothing to the disruptive power of speech on serial recall (Buchner, Irmen, & Erdfelder, 1996; Jones & Macken, 1993; Tremblay, Nicholls, Alford, & Jones, 2000; but see Buchner, Rothermund, Wentura, & Mehl, 2008). For instance, a sequence of auditory-presented numbers is no more disruptive than a sequence of auditory-presented words to serial recall of visually-presented numbers (Buchner et al., 1996). However, the semantic information inherent in speech can enhance the magnitude of the disruption it causes to language-based tasks (in contrast to serial recall). For example, reading comprehension (Martin, Wogalter, & Forlano, 1988; Oswald, Tremblay, & Jones, 2000) and proof reading (Jones, Miles, & Page, 1990) are more sensitive to distraction from speech than to distraction from non-speech sounds. Similar findings have been reported in short-term memory paradigms. Neely and LeCompte (1999) were the first to demonstrate this. They requested participants to view lists of visual to-be-recalled words (e.g., Fruit) while they presented lists of to-be-ignored speech words which either were semantically related to the to-be-remembered words (e.g., other Fruit) or not (e.g., Tools). The speech words that belong to the same semantic category as the to-be-recalled words produced a larger disruption than speech words that belong to a different semantic category (the between-sequence semantic similarity effect). Marsh, Hughes and Jones (2008a, 2009) have extended this research and shown that the semanticity of irrelevant speech is more disruptive than its acoustic properties when meaning form the basis of recall. For example, to-be-ignored words produce more
disruption than non-words or reversed-words when the focal task requires semantic processing. Furthermore, the between-sequence semantic similarity effect arises only when participants are instructed to recall the to-be-recalled words in any order (free recall): The effect is not found when participants attempt to recall words according to their order of presentation (serial recall). Also, the participants tend to recall the semantically-related irrelevant words by mistake, even though they are instructed to ignore items presented in the auditory modality. These intrusion errors are more frequent when the to-be-ignored words are high- as opposed to low-dominance category-exemplars (e.g., “apple” as opposed to “papaya” for the category Fruit) and occur more often when the to-be-ignored items are presented synchronously with the presentation of the to-be-recalled items. This semantic auditory distraction thus embodies (a) an effect of mere meaningfulness (words produce more disruption than non-words), (b) a between-sequence semantic similarity effect (words related to the to-be-recalled items produce more disruption than unrelated words), and (c) promotion of intrusion from non-target items by speech semantically-related to to-be-recalled items. Similar findings have been shown for categorical processing of phonological materials. Specifically, irrelevant-speech items that rime with the to-be-recalled items do indeed increase the magnitude of disruption beyond the mere acoustic properties of sound, but only when the participants are requested to recall the items in free order, not when they are requested to recall the items in order of presentation (Marsh et al., 2008b). Taken together, semantic and phonological similarity between the irrelevant speech and the to-be recalled material do promote disruption when categorical processing of the to-be-recalled material is necessitated (as in free recall), not when serial order processes are necessitated.

Semantic auditory distraction seems to be best explained by an interference-by-process approach to auditory distraction, similar to that applied to the changing-state effect (Marsh et al., 2008a, 2009). The interference-by-process view explains semantic auditory
distraction in terms of (a) deliberate inhibition of non-target competitors activated by speech and (b) breakdown of source monitoring (i.e., a failure to keep track of the source of target and non-target items). Specifically, when meaning is the basis of recall (e.g., when a semantic category name is used as a cue for recall) items are retrieved from a semantic network (e.g., as in free recall but not in serial recall). Higher dominance items compete with lower dominance exemplars for recall, and an inhibition process must prevent high-dominance exemplars from intruding when recall of low-dominance exemplars is required. When irrelevant speech items comprise high-dominance exemplars from the same category as the to-be-recalled items, the high-dominance exemplars must be inhibited to reduce their tendency to win the competition for retrieval. This inhibition process not only affects the activation of to-be-ignored items, but also the activation of to-be-recalled items by spreading inhibition through the semantic network. In other words, the deliberate suppression of non-target category exemplars spreads to target exemplars and reduces the likelihood that to-be-recalled category-exemplars will be retrieved (cf. Neumann & DeSchepper, 1992). Moreover, since the number of intrusions of semantically-related to-be-ignored items into recall is attenuated when the speech is presented during a retention interval, the temporal-contextual information tagged to the memory and speech items contributes to the degree of disruption: When the speech temporally coincides with the memory items, there is a tendency to confuse the source of the materials (a breakdown in source-monitoring; Johnson, Hashtroudi, & Lindsay, 1993).

In contrast to studies of the changing-state effect, there is some indication to suggest that WMC predicts individual differences in susceptibility to semantic auditory distraction. Beaman (2004) demonstrated this relationship using OSPAN as a measure of WMC. He requested participants to view lists of visually-presented to-be-remembered words (e.g., apple, orange) with the task to recall the words in free order, and thereafter he presented lists of to-be-ignored speech words that were semantically related to the to-be-remembered
words (e.g., banana, pear). At recall, low-WMC individuals reported more of the to-be-ignored speech words than high-WMC individuals did. Hence, it seems as if high-WMC individuals are more able to monitor the source of the to-be-ignored speech words (and possibly inhibit the category-exemplars promoted by the speech words), which suggests that the basis of individual differences in susceptibility to semantic auditory distraction is differences in a source-monitoring mechanism (and possibly an inhibition mechanism). The observation that WMC is related to semantic auditory distraction (in contrast to the changing-state effect) is consistent with the finding that old adults are more susceptible to this type of distraction than young adults are (Bell, Buchner, & Mund, 2008). Taken together with the irrelevant sound literature, WMC seems to measure some mechanism that determines people’s susceptibility to distraction from irrelevant semantic information, but not their susceptibility to interference between conflicting order processes.

Now consider another auditory distraction phenomenon. An auditory event that stands out or deviates from the recent auditory past, such as the sound “m” in the sound sequence “c c c m c c c”, disrupts serial recall of visually-presented items. This phenomenon is known as the deviation effect (Hughes, Vachon, & Jones, 2005, 2007; Lange, 2005). Many researchers agree that the deviation effect is caused by attentional capture (e.g., Berti & Schröger, 2003; Hughes et al., 2007; Näätänen, Paavilainen, Rinne, & Alho, 2007), which is believed to be a result of unexpected stimulation. For instance, a sequence of repeated items (e.g., “c c c c c c”) makes us expect that each item is followed by another similar item. When those expectations are violated, as when the sound “m” is presented in the sound sequence “c c c c c m”, an orienting response is elicited (e.g., Siddle, 1991; Sokolov, 1963). The orienting response is accompanied by a redirection of attention towards the unexpected stimulus, away from the focal task, which causes disruption. Initially attentional capture was believed to be a purely stimulus-driven, bottom-up, phenomenon beyond cognitive control,
but a large body of more recent investigations suggests that it can be overridden by cognitive control processes (e.g., Bacon & Egeth, 1994; Berti & Schröger, 2003; Parmentier, Elsley, & Ljungberg, in press; Sussman, Winkler, & Schröger, 2003). If the deviation effect can be overruled by cognitive control, and WMC measures cognitive-control capabilities, then one would expect high-WMC individuals to be less susceptible to the deviation effect.

When engaged in a conversation, hearing one’s own name spoken in the background can capture our attention similar to a deviating sound element in an otherwise repetitive sequence of sounds. This is part of what is known as the “cocktail party phenomenon”. Not all of us demonstrate the cocktail party phenomenon however (Wood & Cowan, 1995). Like with semantic auditory distraction, WMC appears to play a central role in those individual differences. To demonstrate this, Conway, Cowan and Bunting (2001) asked participants to continuously repeat aloud (i.e., shadow) a message presented to one ear while ignoring another message presented to the other ear. The participant’s own name was spoken in the to-be-ignored message at some point during shadowing. The results revealed that people who scored high on the OSPAN task were less likely to report hearing their own name at the end of the session. Furthermore, they were less likely to make shadowing mistakes at the time their name was presented. These findings seem to suggest that high WMC attenuates the potential power of unexpected stimuli to capture attention and they are consistent with the observation that old adults are more susceptible to auditory attentional capture than young adults (Andrés, Parmentier, & Escera, 2006). Based on these results, it seems reasonable to predict that the deviation effect should be attenuated by high WMC.

The evidence for relationships between WMC and auditory distraction reported by Beaman (2004) and Conway et al. (2001) form the basis of the research questions of this thesis, but before moving on to the specific research questions let us go through some of the most influential views of auditory distraction and of WMC.
Accounts of auditory distraction

Interference-by-content views (or structuralistic views)

Baddeley’s phonological loop account is one of the first attempts to explain effects of speech on cognitive performance (e.g., Salamé & Baddeley, 1982). According to this account, the visually-presented to-be-recalled items are recoded from a visual code into a phonological format and maintained in a cognitive structure known as the phonological store. When the to-be-recalled items enter the phonological store, it meets the background speech that has obligatory access to the phonological store. The interference caused by the speech is assumed to be a function of the phonological similarity between the speech material and the to-be-recalled items. In other words, the similarity in phonological content of the speech and the memory materials determines disruption according to this account.

Neath (2000) has proposed another structuralistic account. This account assumes that information in short-term memory is represented by two sets of features. One of these features is modality-dependent whereas the other is modality-independent. Modality-dependent features represent the aspects of the item that are unique to the modality in which it was presented (e.g., its sound if presented in the auditory modality). Modality-independent features, on the other hand, represent aspects of items that are the same regardless of presentation modality (e.g., the semantic meaning of a word presented in the visual or in the auditory modality). The model assumes that speech interferes with memory material because the features of the speech overwrite the features of the visual memory material. The reason why speech wins this competition is because auditory stimuli are assumed to contain more modality-dependent features than visual stimuli.

The interference-by-process view (or functionalistic view)
According to the interference-by-process account, sound interferes with cognitive processes because the sound populates the processes deployed by the primary task. The distinguishing feature of this account is that the nature of the primary task is vital to auditory distraction. More specifically, this view assumes that tasks requiring semantic processing (such as reading comprehension) are disrupted by involuntary semantic processing of speech but not by involuntary order processing (Marsh et al., 2008a, 2009), and tasks requiring order processing (such as immediate serial recall of short word-lists) are disrupted by involuntary processing of the order between perceptually discrete sound elements but not by involuntary processing of semantic or phonological information (Macken et al., 1999). Disruption is hence believed to be a function of the similarity between (a) the deliberate processing of the primary task and (b) the automatic processing of the information in background sound.

The interference-by-process view differs in one important aspect from the interference-by-content view of auditory distraction. According to the interference-by-content view, speech should disrupt short-term memory whether the task instructions are to recall the items in free order or in order of presentation, because the contents of the sound and the contents of the memory materials are the same in both cases. In contrast, the interference-by-process view assumes that serial recall should be susceptible to interference from irrelevant order information, but free recall should not; and free recall of semantically rich memory materials (that emphasize semantic analysis of the memory materials) should be disrupted by irrelevant semantic information, but serial recall should not.

The attentional-resources view and the duplex-mechanism account of auditory distraction

Cowan (1995) has proposed an attentional-resources account of auditory distraction. According to this view, changes in a sound stream deplete a limited pool of
attentional resources. Since these limited resources are also used to entertain the focal task irrelevant sound disrupts performance. This mechanism is a possible explanation to both the changing-state effect and the deviation effect. More specifically, each new sound element in a changing-state sound stream (e.g., “k l m v r q c”) attracts orienting responses which are accompanied by a redirection of attention towards the new stimulus, away from the focal task, which causes disruption. Similarly, a single deviant in an otherwise repetitive sound sequence (e.g., “c c c c c c m”) elicits an orienting response and disrupts performance as a consequence.

At first glance it may seem as if a changing-state sound sequence is just a series of deviant sounds in that each item deviates from the preceding item. However, a number of findings suggest that changing-state and deviating sounds have different effects on cognitive performance (Hughes et al., 2005, 2007) which leans towards the possibility that the changing-state effect and the deviation effect are caused by qualitatively different mechanisms. Because of this, Hughes et al. (2007) have proposed a duplex-mechanism account of auditory distraction according to which the changing-state effect is caused by a conflict between order processes whereas the deviation effect is caused by attentional capture.

Summary and a note on empirical support for the accounts

The accounts of auditory distraction are summarized in Table 1. The weight of empirical evidence supports the interference-by-process view over the interference-by-content views, in showing that the nature of the skill necessitated by the task determines auditory distraction rather than the nature of the task-materials or the nature of the sound-materials (e.g., Macken et al., 1999; Marsh et al., 2008ab). Stated differently, the sound disrupts performance insofar the non-deliberate processing of the sound is in conflict with the skill (or processes) necessitated by the task. The changing-state effect should be held apart from the deviation effect which seems to be qualitatively different, but the evidence for this assumption
is still sparse. It seems as if different types of sound, like speech sounds and non-speech sounds (such as aircraft noise) have different effects on cognitive performance insofar they (a) map onto the processes necessitated by the task differently or (b) capture attention through unexpected sound stimulation differently.

**Table 1. Summary of different views of auditory distraction.**

<table>
<thead>
<tr>
<th>View</th>
<th>Mechanism explaining auditory distraction</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phonological loop account</td>
<td>Phonological interference</td>
<td>Salamé &amp; Baddeley (1982)</td>
</tr>
<tr>
<td>Feature model</td>
<td>Feature overwriting</td>
<td>Neath (2000)</td>
</tr>
<tr>
<td>Interference-by-process account</td>
<td>Conflicting processes</td>
<td>Macken et al. (1999)</td>
</tr>
<tr>
<td>Attentional-resources account</td>
<td>Depletion of attentional resources</td>
<td>Cowan (1995)</td>
</tr>
<tr>
<td>Duplex-mechanism account</td>
<td>Conflicting processes and attentional capture</td>
<td>Hughes et al. (2007)</td>
</tr>
</tbody>
</table>

**Views of working memory capacity**

As already mentioned, the typical way to operationalize WMC is to employ complex-span tasks. The first complex-span task to be introduced was the “reading span task” by Daneman and Carpenter (1980). This task is similar to the OSPAN task, but it includes a reading-part instead of an operation-part. Initially, researchers believed that WMC (as measured with reading span) reflects individual differences in a domain-specific pool of cognitive resources. For instance, reading span was assumed to measure the capacity to process linguistic information since it involves reading processes. Later however, researchers found that reading span predicts performance across other domains as well, and they found that slight modifications of the original complex-span task (such as OSPAN) also predict performance across a wide range of domains not evidently from the same skill-domain as the complex-span tasks themselves (see Engle, 2002 for a review). These findings have led to more domain-general views of WMC.

One of those perspectives is the inhibitory view by Hasher and Zacks (1988). According to this view, what differs between individuals with high and low WMC is an inhibitory mechanism. That is, WMC is viewed as a limited and domain-general pool of
resources that mainly can be used to inhibit the processing of extraneous and endogenous task-irrelevant stimuli and irrelevant behavioural responses. The inhibitory view has received much support, especially from studies of elderly (for a review, see Lustig et al., 2008).

Another perspective of WMC called the *executive attention* view proposes that WMC measures a limited and domain-general pool of resources that can be used to control attention, by constraining the attentional scoop to task-relevant information and resist distraction from task-irrelevant information (Engle, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2001). In support for this claim, it has been shown that individual differences in WMC predict people’s performance on tasks that require attention-control and very low memory demands (Kane et al., 2001; Heitz & Engle, 2007; Redick & Engle, 2006; Unsworth et al., 2004).

A third and more recent view of WMC, that may be called the *primary and secondary memory view*, has been proposed by Unsworth and Engle (2007). They reviewed evidence that suggest that high- and low-WMC individuals differ in the ability (a) to maintain memory representations actively in primary memory in the presence of distraction and (b) to limit the search for items in secondary memory once they have been displaced from primary memory. For example, Kane and Engle (2003) had high- and low-WMC individuals perform a colour-word Stroop task. The results revealed that low-WMC individuals make more response errors to incongruent trials (i.e., when word and ink does not match) than high-WMC individuals, but only when the incongruent trials are relatively infrequent. The authors suggested that incongruent trials reminded the participants of the task-goal, so when incongruent trials are common, there is no difference between the two groups. On the other hand, when the participants must keep the task-goal representation in primary memory across several trials without reminders, as when incongruent trials are infrequent, high-WMC
individuals manage to keep the task-instructions active in primary memory and respond accurately to incongruent trials, whereas low-WMC individuals forget what to do.

**Summary and discussion**

The views of WMC are summarized in Table 2. It is quite clear that complex-span tasks measure some fundamental cognitive-control mechanism (or several mechanisms) capable of underlying a wide range of higher-order cognitive abilities. This mechanism may be the ability to inhibit the irrelevant (Lustig et al., 2001), the ability to control attention (Engle, 2002), or the ability to maintain items in primary memory in presence of distraction and to limit the search for items in secondary memory (Unsworth & Engle, 2007). However, all of these views suggest that complex-span tasks should predict basically any cognitive activity. Because of this, it is very difficult (if not logically impossible) to tease them apart. For instance, the negative relationship between WMC and the probability to detect one’s own name in a to-be-ignored speech stream (Conway et al., 2001) fits well with the assumption that WMC measures capacity to constrain attention to task-relevant information (the to-be-attended stream in this case) and with the assumption that WMC measures capacity to inhibit irrelevant information (the to-be-ignored stream in this case). It is clearly not possible to decide which view is accurate (or if perhaps both views are accurate). Heitz and Engle (2007) encountered similar problems when they discussed why high- and low-WMC individuals differ on the flanker task and concluded that “although we argued against a general inhibition view … the data presented here cannot dissociate a constraining field of activation from a spreading field of inhibition. Essentially, both views make identical predictions …” (p.232). These examples demonstrate the impossibility to disentangle the executive attention view and the inhibition view. Capacity theories such as these are also stubbornly difficult to falsify (which draws the theories towards becoming unscientific) and are often troubled by a self-
The self-reinforcing nature of these theories arises through what Popper (1959) called “the fallacy of affirming the consequence”. When researchers aim to test the hypothesis that high WMC, for example, predicts the speed with which participants can count objects on a screen because WMC measures the capability to control attention, it is logically impossible to refute the WMC account regardless of the findings. If a WMC effect is found, it is concluded that counting requires attention control (i.e., WMC). If no WMC effect is found, then nothing other than assuming that “WMC was not needed” can explain this absence, and therefore the WMC account becomes irrefutable: Any absence of an expected correlation between complex-span scores and another variable leads to the conclusion that the WMC account is correct and the other task/phenomenon is not dependent on cognitive control after all. The same can be said about the absence of a relationship between WMC and the irrelevant sound effect. This absence may, at most, say that the role of distraction in WMC must be better specified. Taken together, it is quite clear that a new view of WMC is needed.

Table 2. Summary of different views of working memory capacity.

<table>
<thead>
<tr>
<th>View</th>
<th>Mechanism believed to underlie difference in WMC</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inhibitory view</td>
<td>Inhibition</td>
<td>Hasher &amp; Zacks (1988)</td>
</tr>
<tr>
<td>Executive attention view</td>
<td>Attentional control</td>
<td>Engle (2002)</td>
</tr>
<tr>
<td>Primary and secondary memory view</td>
<td>Maintenance of items in primary memory and search for items in secondary memory</td>
<td>Unsworth &amp; Engle (2007)</td>
</tr>
</tbody>
</table>

Summary of reports

Based on the findings reported by Beaman (2004) and by Conway et al. (2001), it seems safe to conclude that individual differences in WMC do indeed underlie at least some type of auditory distraction. The purpose of the studies summarised in this thesis was to investigate the relationship between WMC and auditory distraction in more detail.
Research questions

Report I

The research questions of Report I were: Can measures of more specific cognitive processes explain the relationship between working memory capacity and the effects of speech on reading comprehension? This research question promoted the use of a task with the capability to disentangle separate sub-processes covered by the WMC construct. The main hypothesis of Report I was: The capability to suppress potentially relevant, but ultimately irrelevant, materials is the mechanism responsible for the relationship between WMC and effects of speech on reading comprehension.

Report II

The research question of Report II was: Can the concept “working memory capacity” be broken down into functionally distinct sub-processes? This research questions was approached by using different complex-span task with the capability to measure different sub-processes covered by the WMC construct. Two hypotheses were tested: First, the capability to exclude potentially relevant but ultimately irrelevant materials from the memory-set underlies the relationship between WMC and semantic auditory distraction; second, the capability to suppress previously relevant but no longer relevant items from the memory set (which is known to underlie efficient reading comprehension) is not related to semantic auditory distraction.

Report III

The research questions of Report III were: Can a relationship between working memory capacity and auditory distraction be found in more ecological settings? Is working memory capacity more strongly related to distraction from some type of sound than from
others? Specifically, is working memory capacity more strongly related to the effects of aircraft noise or to the effects of speech on prose memory? To address these questions, the effects of ecologically relevant noise (aircraft noise and meaningful speech) on school adolescents’ prose memory were investigated. It was hypothesized that high WMC would attenuate the effects of speech and the effects of aircraft noise on prose memory. Whether or not either of these relationships would be stronger than the other was an open question.

Report IV

The research questions of Report IV were: Is the deviation effect and the changing-state effect caused by the same or by different mechanisms? Does high working memory capacity attenuate the deviation effect but not the changing-state effect? Based on the findings that high WMC attenuates the probability to detect one’s own name spoken in a to-be-ignored speech stream and that attentional capture can be overruled by cognitive control, it was hypothesized that the deviation effect should be attenuated by high WMC. Since the changing-state effect seems to be a consequence of perceptual and automatic processes, it was hypothesized that WMC is unrelated to the changing-state effect.

Method

Apparatus and materials

Sounds. The effects of speech on reading processes were measured in Report I, II and III. The irrelevant speech was recorded in an echo-free room. The speech consisted of a story about a fictitious culture called “the Ansarians” told by a male actor. Report III also included aircraft noise. Sounds from different airborne aircrafts were recorded and filtered with computer software as if they had passed through a brick wall. The purpose of this manipulation was to make the sound perceived as indoors. All sounds were played back
through headphones at approximately 65 dB(A). Spoken-letter and tone sequences were used to produce deviation effects and changing-state effects in Report IV.

**Working memory capacity tasks.** Three different tasks were used to operationalize individual differences in WMC. A number updating task, originally developed by Carretti, Cornoldi, and Pelegrina (2007), was used in Report I and Report II. In this task, sequences of two-digit numbers are presented to the participants one at the time (e.g., 47 23 58 63 49 30 52 41 67 45), and their goal is to recall the three numbers in the sequence with the lowest arithmetic values. At recall, the participants can make two types of errors. “Immediate intrusions” measure recollection of items that should never have been added to the set of relevant items (e.g., 45 in the example), whereas “delayed intrusions” measure recollection of items that were relevant when added to the memory set, but should subsequently have been suppressed from the set before recall (e.g., 49 in the example). This type of updating task is a valid measure of WMC (Schmiedek, Hildebrandt, Lövdén, Wilhelm, & Lindenberger, 2009), although its structure is different from that of complex-span tasks. The number updating task was preferred to typical WMC measures because it has the advantage of being able to disentangle two cognitive capabilities. Specifically, immediate intrusions are believed to measure the capability to suppress or exclude potentially relevant but ultimately irrelevant materials from the memory set; whereas delayed intrusions are believed to measure the capability to suppress or delete previously relevant items held in the memory set.

A traditional complex-span task called OSPAN was used to measure WMC in Report II, III, and IV. In this task, the participants view sets of operation-word strings (e.g., “Is \((4 \times 3) + 5 = 17?\) DOG”) with the task to respond “yes” or “no” to the operation and to remember the word for later recall. After responding to a set of those operation-word strings, the participants are probed to recall the words in order of presentation. This task was chosen
to stay consistent with previous studies of WMC and auditory distraction (Beaman, 2004; Conway et al., 2001). A new task called size-comparison span (SICSPAN) was also used to measure WMC in Report II. This task is structurally similar to OSPAN, but instead of operation-word strings, the participants view comparison-word strings (e.g., “Is JACKET larger than SHOE? SOCK”). The participants are requested to answer “yes” or “no” to the question and to remember the last word (i.e., “SOCK” in the example above) for later recall. After responding to a set of questions, the participants write down the to-be-recalled words in order of presentation. In SICSPAN, the participants might recall words that are part of the questions rather than presented as to-be-recalled words. This type of error is called “current-list intrusions”. Current-list intrusions are believed to measure the capability to exclude potentially relevant but ultimately irrelevant materials from the memory set (i.e., an inclusion/exclusion mechanism) and as such are functionally equivalent to the immediate intrusion errors of the number updating task. The purpose of developing the SICSPAN task was twofold. First, it makes it possible to obtain an individual measure of the inclusion/exclusion mechanism (and hence address the question if this capability underlies the relationship between WMC and auditory distraction) in contrast to other complex-span tasks like OSPAN. Second, it solved methodological problems with the number updating task by making the measure of the inclusion/exclusion mechanism more reliable.

Reading tasks. Two reading comprehension tasks were used in Report I. The structure of the two tasks (but not the content) was identical. The participants read short paragraphs and answered multiple-choice questions that concerned the meaning of the written text, having the text available for review when answering the questions. This task was designed to frame the effects of speech on ongoing reading processes without relying heavily on long-term memory processes, in contrast to previous studies of effects of speech on “reading comprehension” (Martin et al., 1988; Oswald et al., 2000). One of the two tasks was
performed in silence and the other was performed against a background of speech in order to obtain a measure of the effects of speech on reading comprehension. Two prose memory tasks were used in Report II and III. As with the reading comprehension tasks, the structure of the two tasks (but not the content) was identical. Each task consisted of two phases. In the first phase, the participants read 10 short paragraphs about a fictitious culture. Each paragraph was presented for 60 sec. After presentation, the participants indicated if they had been able to read the whole paragraph (to allow for the possibility to exclude paragraphs not completely read in the analyses). In the second phase, they answered open-ended questions about facts explicitly stated in the first phase. Hence, in the prose memory task the participants had to retain the materials in memory for later recall. One of the two tasks was performed in silence. In the other task, each paragraph was accompanied with sound, but all questions were presented and answered in silence. This procedure ensured that any effect of sound was limited to processes taking place at the reading phase of the task.

**Visual-verbal serial recall.** A typical visual-verbal serial short-term memory task was used in Report IV. Sequences of eight digits were presented visually to the participants and their task was to recall the digits in order of presentation immediately after seeing the last digit. Each digit was displayed for 350 ms and the inter-stimulus interval was 400 ms. Each trial was accompanied by one of three types of sound sequences (hence there were no silent condition). A steady-state sound sequence consisted of 21 identical items (spoken letters in one experiment and tones in another experiment). A changing-state sound sequence consisted of 21 items taken from a set of 4 different items (spoken letters or tones depending on experiment). No two successive items were identical. A deviant sound sequence was identical to the steady-state sound sequences with the exception that item number 11 (the item in the middle of the sequence) was changed so as to deviate from the other items.
The participants performed two blocks of 30 serial recall trials. In one block, the first two trials were steady-state trials and used to familiarize the participants with the task (performance was excluded from the analyses). The remaining 28 trials consisted of 22 steady-state trials and 6 deviant trials. The deviant trials occurred at trial number 5, 9, 15, 21, 24 and 29. The other block was identical, except that changing-state sound sequences were played instead of deviant sound sequences at trial number 5, 9, 15, 21, 24 and 29. The two blocks were separated by a self-paced pause.

**Design and procedure**

All studies used the same basic quasi-experimental design. That is, all studies measured an effect of sound on cognitive performance by manipulating a within-subject variable. A within-subject manipulation was not only preferred for statistical reasons, but also necessary to obtain a person specific measure of the magnitude of auditory distraction. In line with this choice of design, the order of the tasks used to measure auditory distraction and the order of the sound conditions were counterbalanced between participants. In addition, measures of individual differences in cognitive functioning were used to predict the magnitude of auditory distraction. These individual differences constitute between-subject, non-randomized, variables and they are the reason why quasi-experimental rather than purely experimental designs were used. All data collection was made with computers. The participants of Report I, II and IV were all university students and they sat alone in a silent room in front of the computer with headphones attached. The participants of Report III attended upper-secondary school and also performed all tasks using computers, but they were tested in groups of about 20 individuals to reach a higher ecological validity. All participants worked individually and they did not interact during the experiment proper.
Summary of results

Report I: Individual differences in susceptibility to the effects of speech on reading comprehension

The first report investigated the relationship between WMC and the effects of speech on reading comprehension. The number updating task was used to measure WMC rather than traditional tasks such as OSPAN, since it has the advantage of being able to tease apart two specific cognitive mechanisms. Immediate intrusion errors—committed when an item that never should have been considered for recall was still recalled—were believed to measure the capacity to suppress new—potentially relevant but ultimately irrelevant—information from memory. Delayed intrusion errors—committed when an outdated item was recalled—were assumed to measure the capacity to suppress once relevant but subsequently irrelevant information from memory. Correct responses on the number updating task, on the other hand, were used as a typical measure of WMC.

Table 3. Effects of speech on reading comprehension: Correct answers (scores) and time taken to complete the task (minutes)

<table>
<thead>
<tr>
<th>Measure</th>
<th>Silence</th>
<th></th>
<th>Speech</th>
<th></th>
<th>F</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct answers</td>
<td>M = 11.55, SD = 2.24</td>
<td>M = 10.58, SD = 2.93</td>
<td>6.34*</td>
<td>.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minutes</td>
<td>M = 14.22, SD = 3.00</td>
<td>M = 14.41, SD = 2.56</td>
<td>&lt;1</td>
<td>.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* $p < .05$

As can be seen in Table 3, background speech reduced reading comprehension task scores. Furthermore, regression analyses revealed that participants who scored high on the number updating task (i.e., high correct recall) were less susceptible to this disruption, $\beta = .36, t = 2.08, p < .05$. Importantly, this relationship was explained by the immediate intrusion errors. Immediate intrusions predicted the effects of speech on reading comprehension, $\beta = -.49, t = -3.55, p < .01$, and when immediate intrusions were statistically controlled for, correct recall no longer predicted disruption, $\beta = -.02, t = -0.09, p = .93$, but immediate intrusions did.
$\beta = -.43, t = -2.05, p < .05$. Delayed intrusions were unrelated to the effects of speech on reading comprehension. The main conclusion is that the capacity to exclude or suppress new (potentially relevant but ultimately irrelevant) materials from memory (as measured by immediate intrusion errors) underlies the relationship between WMC and the effects of speech on reading comprehension. In other words, the capacity to exclude new materials from memory is the sub-process covered by the WMC construct that is responsible for the WMC constructs’ relationship to distraction. These results are neither easy to assimilate with the executive attention view of WMC nor with the inhibitory view, because the results suggest that WMC actually measures functionally distinct sub-processes (one related to auditory distraction and one not) or distinct pools of resources, not a single construct or a single pool of domain-general resources.

**Report II: A sub-process view of working memory capacity: Evidence from effects of speech on prose memory**

The second report intended to introduce and outline a new perspective on the nature of working memory capacity. The report included two experiments. Experiment 1 was designed to conceptually replicate the findings of Report I, but also to extend those findings to the effects of speech on prose memory. Experiment 2 intended to conceptually replicate the results of Experiment 1, but with a new task called size-comparison span that was designed to overcome some methodological problems with the number updating task.

**Table 4.** Participants’ score on the prose memory task as proportions of paragraphs completely read

<table>
<thead>
<tr>
<th>Prose memory</th>
<th>Silence</th>
<th>Speech</th>
<th>Difference</th>
<th>$F$</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M$ $SD$</td>
<td>$M$ $SD$</td>
<td>$M$ $SD$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 1</td>
<td>.61 .17</td>
<td>.49 .19</td>
<td>.11 .11</td>
<td>22.84**</td>
<td>.51</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>.54 .15</td>
<td>.47 .17</td>
<td>.07 .12</td>
<td>12.25**</td>
<td>.23</td>
</tr>
</tbody>
</table>

Note. The $F$-values are based on within-subject designs

** $p < .01$
As can be seen in Table 4, speech disrupted prose memory across both experiments. Both experiments found correlations between one type of error committed in the WMC tasks (believed to measure the capacity to exclude irrelevant materials from memory) and the effects of speech on prose memory. Furthermore, Experiment 2 found that the correlation between correct recall on size-comparison span (and OSPAN) was related to the effects of speech on prose memory, but this correlation disappeared when the capacity to exclude irrelevant materials were controlled for (i.e., an inclusion/exclusion mechanism). Prior-list intrusions and delayed intrusions, believed to measure the capacity to delete or suppress outdated information from memory (i.e., a deletion/suppression mechanism), were unrelated to disruption. These results are summarized in Tables 5 and 6.

**Table 5. Hierarchal regression analyses of the relation of individual measures from the number updating task to the effects of speech on prose memory in Experiment 1**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Relation to prose memory disruption</th>
<th>β*</th>
<th>t</th>
<th>(\Delta R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predictors entered alone</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immediate intrusions</td>
<td>-.27</td>
<td>-2.21*</td>
<td>.07</td>
<td></td>
</tr>
<tr>
<td>Delayed intrusions</td>
<td>.04</td>
<td>0.26</td>
<td>&lt;.01</td>
<td></td>
</tr>
<tr>
<td>Number updating score</td>
<td>.26</td>
<td>2.10*</td>
<td>.06</td>
<td></td>
</tr>
<tr>
<td>Predictors entered simultaneously</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immediate intrusions</td>
<td>-.27</td>
<td>-2.14*</td>
<td>.07</td>
<td></td>
</tr>
<tr>
<td>Delayed intrusions</td>
<td>.01</td>
<td>0.11</td>
<td>&lt;.01</td>
<td></td>
</tr>
<tr>
<td>Predictors entered simultaneously</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immediate intrusions</td>
<td>-.17</td>
<td>-1.06</td>
<td>.02</td>
<td></td>
</tr>
<tr>
<td>Number updating score</td>
<td>.14</td>
<td>0.85</td>
<td>.01</td>
<td></td>
</tr>
</tbody>
</table>

* p < .05

* Standardized regression coefficient for predictors of prose memory in the irrelevant speech condition after control for prose memory in the silent condition and condition order

**Table 6. Hierarchal regression analyses of the relation of individual measures from size-comparison span (SICSPAN) and operation span (OSPAN) to the effects of speech on prose memory in Experiment 2**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Relation to prose memory disruption</th>
<th>β*</th>
<th>t</th>
<th>(\Delta R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predictors entered alone</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SICSPAN score</td>
<td>.34</td>
<td>3.34**</td>
<td>.10</td>
<td></td>
</tr>
</tbody>
</table>
The results support a sub-process view of WMC. According to this view, WMC is a compound of functionally distinct sub-processes (or distinct pools of resources) that can be measured by the errors participants make when undertaking the WMC task. The results of Report II show that one of those sub-processes (the inclusion/exclusion mechanism) is related to the effects of speech on prose memory, whereas another sub-process (the deletion/suppression mechanism) known for its involvement in reading comprehension is not. Furthermore, the inclusion/exclusion mechanism seems responsible for the relationship between WMC and disruption. These results are not easily accommodated by single-structure views of WMC (such as the executive attention view and the inhibitory view). Instead, the results seem to rest more easily within a multiple-structure view of WMC such as the sub-process view since it appears as if WMC covers functionally distinct sub-processes.

Report III: Effects of aircraft noise and speech on prose memory: What role for working memory capacity?
The third report was intended to extend previous findings to more ecological settings. To this end, adolescents attending upper-secondary school (16-18 years of age) were recruited as participants and tested in two experiments in their ordinary classrooms. As can be seen in Table 7, Experiment 1 found that speech disrupts prose memory compared with silence, but aircraft noise does not. However, WMC (as measured by OSPAN) was related to the effects of aircraft noise on prose memory, $\beta = .32, t = 2.51, p < .05$, but not to the effects of speech on prose memory, $\beta = .19, t = 0.75, p = .46$. Because of this, speech seems more disruptive than aircraft noise to prose memory and WMC seems more strongly related to the effects of aircraft noise than to the effects of speech. Experiment 2 supported these conclusions by demonstrating larger effects of speech on prose memory and a relationship between WMC and the difference between the effects of speech and aircraft noise on prose memory, $\beta = .27, t = 2.14, p < .05$.

Table 7. Participants' score on the prose memory task as proportions of questions for paragraphs completely read

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$M$</th>
<th>$SD$</th>
<th>$M$</th>
<th>$SD$</th>
<th>$M$</th>
<th>$SD$</th>
<th>$F$</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aircraft noise</td>
<td>.24</td>
<td>.20</td>
<td>Silence</td>
<td>.28</td>
<td>.22</td>
<td>.04</td>
<td>.14</td>
<td>1.67</td>
</tr>
<tr>
<td>Experiment 1b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speech</td>
<td>.17</td>
<td>.11</td>
<td>Silence</td>
<td>.28</td>
<td>.16</td>
<td>.11</td>
<td>.16</td>
<td>10.44*</td>
</tr>
<tr>
<td>Experiment 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speech</td>
<td>.42</td>
<td>.14</td>
<td>Aircraft noise</td>
<td>.48</td>
<td>.15</td>
<td>.05</td>
<td>.12</td>
<td>8.45*</td>
</tr>
</tbody>
</table>

Note. All experiments are within-subject. The participants in Experiment 2 were older and attended a school program different from the other participants which may explain the large between-experiment differences in prose memory score. * $p < .01$

Altogether, the results indicate that sounds with semantic meaning (i.e., speech) is more disruptive to tasks that require semantic processing (i.e., prose memory in this case) compared with other types of sound, probably due to a conflict between deliberate processing of the semantic meaning of the prose material and the automatic processing of the semantic
meaning of the sound. Moreover, WMC is more strongly related to disruption caused by aircraft noise than to disruption caused by speech, perhaps because their effects on prose memory are qualitatively different. One possibility is that interference-by-processes underlie the effects of speech on reading processes, whereas aircraft noise (being a sound without semanticity) disrupts reading by attentional capture.

Report IV: High working memory capacity attenuates the deviation effect but not the changing-state effect: Further support for the duplex-mechanism account of auditory distraction

The fourth report intended to tease apart the mechanisms that underlie the deviation effect and the changing-state effect. A short-term serial recall task was used to obtain participant-specific measures of the magnitude of the deviation effect and the changing-state effect. In Experiment 1, spoken letters were used to produce the effects (Figure 1). In Experiment 2, sinus-wave tones were used instead of speech sounds (Figure 2). A relationship between WMC (as measured by OSPAN) and the deviation effect was found across both experiments (Figures 3 and 4). Neither experiment could support a relationship between WMC and the changing-state effect. In fact, the correlation between WMC and the deviation effect was significantly different from the correlation between WMC and the changing-state effect in Experiment 2. The results indicate (a) that WMC is related to some, but not all, types of auditory distraction, and (b) that the deviation effect and the changing-state effect are caused by qualitatively different mechanisms. Hence, the results support the duplex-mechanism account of auditory distraction over the attentional-resources account. Furthermore, since tones produced reliable disruption of the visual-verbal task, the results cannot be explained by interference-by-content views of auditory distraction because the sound and the memory materials do not share similar content.
Figure 1. Mean percentage of items correctly recalled in each serial position in the steady-state condition in the deviant block (SS-DB), the steady-state condition in the changing-state block (SS-CSB), the deviant condition (D) and the changing-state condition (CS) in Experiment 1. Error bars show standard errors of mean.
Figure 2. Mean percentage of items correctly recalled in each serial position in the steady-state condition in the deviant block (SS-DB), the steady-state condition in the changing-state block (SS-CSB), the deviant condition (D) and the changing-state condition (CS) in Experiment 2. Error bars show standard errors of mean.

Figure 3. The correlation between operation span score and the deviation effect (calculated as the difference between serial recall score in the steady-state condition and serial recall score in the deviant condition) in Experiment 1.
Discussion

Implications for theories of auditory distraction

The duplex-mechanism account of auditory distraction (Hughes et al., 2007) suggests that some effects are caused by attentional capture (e.g., the deviation effect) whereas others are caused by interference between similar processes (e.g., the changing-state effect). The findings from the studies in this thesis are in agreement with this view. Auditory distraction seems to be a function of at least two different mechanisms. One is the efficiency with which people process the order between perceptually discrete sound events. This mechanism underlies individual differences in susceptibility to the changing-state effect (Macken et al., 2009) and its involvement is therefore restricted to tasks which necessitate serial-order processing (cf. Macken et al., 1999). The other mechanism is reflected in working memory capacity (WMC). This mechanism seems to be involved in a wider range of phenomena including disruption of short-term recall of semantic information (Beaman, 2004), the cocktail party phenomenon (Conway et al., 2001), the deviation effect (Sörqvist, in press), effects of speech on reading processes (Sörqvist et al., 2010a, 2010b) and effects of aircraft
noise on prose memory (Sörqvist, 2010). However, WMC is unrelated to the changing-state effect (Beaman, 2004; Elliott & Cowan, 2005; Sörqvist, in press; see also Ellermeier & Zimmer, 1997; Macken et al., 2009; Neath et al., 2003) which suggests that the two mechanisms are functionally independent.

Beaman (2004) suggested two other mechanisms that may be involved in semantic auditory distraction: inhibition of irrelevant information and failure of source monitoring. The idea that a source monitoring mechanism contributes to semantic auditory distraction is consistent with the finding that the number of intrusions from speech into the recall protocol is greater when the target materials and the speech materials are presented simultaneously in comparison to when the speech materials are presented during a retention interval (Marsh et al., 2008a). However, the studies reported here provides reasons to doubt that “source monitoring” adequately describes the underlying mechanism. Immediate intrusion errors in the number updating task are related to auditory distraction (e.g., Sörqvist et al., 2010ab) and this type of error cannot be explained by failure in source monitoring since all numbers in the number updating task have the same source at presentation. A perhaps more specific alternative would be to frame this relationship in terms of a relevance monitoring mechanism (i.e., a mechanism responsible for excluding information that does not reach a certain relevance criterion from the memory-set). A relevance monitoring mechanism (or the capacity to respond appropriately to task-relevant materials and block irrelevant materials) may also explain phenomena other researchers have addressed source monitoring to explain. A mechanism responsible for the gating of information into working memory is also discussed in other recent work, mainly in the field of neurosciences (e.g., Vogel, McCollough, & Machizawa, 2005), and it is believed to contribute to what limits the storage capacity of working memory in general (McNab & Klingberg, 2008).
The nature of the mechanism reflected by WMC requires further discussion. On the one hand, WMC attenuates attentional capture by unexpected auditory stimulation (Conway et al., 2001; Sörqvist, in press). On the other hand, WMC is related to semantic interference (Beaman, 2004; Sörqvist et al., 2010ab). Are those relationships caused by a single mechanism or are they caused by several mechanisms juxtaposed under the WMC construct? To answer this question, it could be useful to analyse the complex-span tasks used to operationalize WMC in more detail. For instance, in the OSPAN task, the participants move back and forth between processing operations (e.g., “Is (4 - 2) / 2 = 1?”) and storing/rehearsing words (e.g., “SNAIL”). Hence, good performance requires attention to be divided (or shifted) between the two parts of the task. Furthermore, the participants must avoid confusion among the items encountered in the processing-part of the task with those presented in the memory-part of the task. A participant’s OSPAN score should therefore reflect a conglomerate of the work by at least two mechanisms: one responsible for the ability to divide or shift attention between two concurrent tasks and one responsible for the ability to exclude irrelevant materials from the memory-set. A low OSPAN score could therefore reflect a poor ability to divide attention, a poor ability to exclude irrelevant materials, or both. This way, the same OSPAN score can be related to a range of phenomena for qualitatively different reasons (cf. the sub-process view of WMC by Sörqvist et al., 2010b). Based on this reasoning, a divided-attention mechanism might be responsible for the relationship between WMC and attentional capture whereas an inclusion/exclusion mechanism (i.e., a relevance monitoring mechanism) could underlie the relationship between WMC and semantic auditory distraction. If accepted, these ideas propose that at least three mechanisms contribute to auditory distraction: conflict between similar processes, attentional capture, and the failure to respond accurately to a stimulus depending on whether or not it reaches a certain task-relevance criterion (e.g., to include relevant and exclude irrelevant materials from the
memory-set). It should be noted however that the nature of the third mechanism is not at all clear at present.

**Implications for theories of working memory capacity**

A recent theory proposes that WMC measures the capacity for active maintenance in primary memory and the size of “controlled search” within secondary memory (Unsworth & Engle, 2007). This view implies that WMC reflects at most two related processes, which runs directly contrary to other, related work on “executive functions”. In the executive-functions research tradition, researchers presume that no single task measures a single process (i.e., a task is not process-pure). Rather, cognitive tasks are believed to measure various sub-processes or “executive functions” (Miyake et al., 2000) and the contributions from individual sub-processes are relative and depend on the nature of the task (cf. Roediger, Gallo, & Geraci, 2002). The sub-process view of WMC introduced and outlined in this thesis (Sörqvist et al., 2010ab) was developed in light of the observation that complex-span tasks (the family of tasks usually used to operationalize WMC) might not be process-pure and therefore there is reason to assume that complex-span scores do not measure a single pool of resources (e.g., inhibition or attention-control). According to the sub-process view, WMC is not a unitary construct. Instead it is viewed as a compound of a variety of cognitive capabilities. When viewed this way, WMC can be related to other constructs for a variety of different reasons. For instance, WMC might correlate with some capability (e.g., resistance to semantic auditory distraction; Beaman, 2004; Beaman, Bridges, & Scott, 2007; Sörqvist et al., 2010ab) because the task used to measure WMC requires the action of a critical sub-process (e.g., an inclusion/exclusion mechanism) that is also involved in that particular capacity. Similarly, the same WMC measure might correlate with some other capability (e.g., reading comprehension) because another sub-process (e.g., a deletion/suppression mechanism) is
involved in that particular capability. These assumptions have been supported by a handful of experiments (Carretti, Cornoldi, De Beni, & Romanò, 2005; Sörqvist et al., 2010ab) which suggests that WMC covers at least two functionally distinct sub-processes, one related to auditory distraction, the other to reading comprehension.

The sub-process view is neither in disagreement with old nor contemporary views of WMC. For instance, Unsworth and Engle’s (2007) proposition that low-WMC individuals suffer from an inefficient search of items in secondary memory may indeed explain why WMC is related to (some) higher-order cognitive capabilities. The distinguishing feature of the sub-process view is that WMC is related to different phenomena for different reasons (including retrieval from secondary memory). The sub-process view is not a theory that intends to explain the nature of the sub-processes covered by the WMC construct. It is rather a framework for how correlations can be understood and it intends to show that the sub-processes should be the subject for scientific enquiry, not WMC in toto. Its intention is not to postulate anything about the nature of the cognitive processes that underlies complex-span performance; its intention is to postulate that the WMC concept clouds the possibility to understand individual differences in cognitive functioning, that the WMC concept is counterproductive to scientific progress, and it should be eliminated from basic science if a superior predictive power can be obtain with more process-pure tasks than complex-span tasks. In other words, if any relationship between WMC and some cognitive capability actually is a relationship between individual, and potentially measureable, sub-processes and those cognitive capabilities, the WMC concept per se is not required to explain individual differences in cognitive functioning.

Ever since the seminal paper by Turner and Engle (1989), there is little debate concerning whether different complex-span tasks measure different processes (but see Kane et al., 2004). Instead, it seems as if most researchers use the OSPAN task without considering
the possibility that it contributes with unique variance to the WMC construct. In contrast, it follows from the sub-process view that the way WMC is operationalized is highly important. The sub-process view conceives WMC as a **dynamic construct**, strictly dependent on the way in which it is measured, since different compositions of sub-processes make up different versions of the WMC construct (i.e., different pools of resources). For instance, correct recall on the original version of the size-comparison span task predicts the effects of speech on prose memory (Sörqvist et al., 2010b). In this version of the task, all words within a trial were taken from the same semantic category which, according to the sub-process view, should influence the correlative properties of the recall scores. If the semantic relatedness of the words within lists is reduced, this should influence the predictive power of the recall scores, because the task no longer requires the involvement of a mechanism that resolve confusion among semantically related materials. In this way, specific sub-processes can be isolated by manipulating the task demands of the complex-span tasks. These methodological considerations open for the possibility to investigate the reason why complex-span tasks correlates with other variables by manipulating the requirement of different sub-processes (cf. Moscovitch, 1992) and call for new investigations in the future. One approach would be to specify and separate individual sub-processes in structural equation models, and study how the models change as a consequence of manipulations to the complex-span tasks.

**Limitations and future directions**

One limitation of the present work is the lack of non-speech sound conditions in Report I and II. Without a comparison between the effects of speech and an appropriate non-speech sound (such as spectrally rotated speech), it is impossible to determine if the disruption is caused by the lexico-semantic information of the speech material or something else. Because of this, it is impossible to know if the relationships found between WMC and effects
of speech on reading comprehension/prose memory is a relationship between WMC and semantic auditory distraction or a relationship between WMC and some other type of auditory distraction (such as attentional capture). Future research should disentangle these possibilities.

Another major limitation of the work presented here is that it relies heavily on the so-called inclusion/exclusion mechanism even though it is unclear what it actually does. For instance, it might be responsible for blocking items from entering a memory-set, or it might be responsible for some kind of inhibition process acting on irrelevant items, or it might be responsible for resolving cognitive conflict by stopping goal-directed behaviour of being attributed to wrong stimuli. Any of these possibilities seems just as plausible from what is known at present. One way to proceed with this line of research is to investigate the actual processes operating on current-list intrusions in the SICSPAN task more carefully. For instance, it is possible to measure if the to-be-excluded items in the SICSPAN task actually undergo inhibition by borrowing a technique from the negative priming literature (Figure 5). In a typical negative priming experiment, the participants are probed to name a visual object (say a picture of a “dog”) while another visual object is superimposed on the target object (say a picture of a “lion”). The non-target object acts in this case as a distractor. On the subsequent trial (called trial n + 1), the non-target items on the previous trial (“lion” in this case) becomes the target item. Response latencies on the n + 1 trial are prolonged in comparison to a control trial. This is evidence of the assumption that the non-target object on trial n (“lion”) was inhibited, resulting in slower response times when the previous non-target object becomes the target. By using an analogy of this experimental procedure and the SICSPAN task it should be possible to measure whether or not the current-list intrusions actually undergo inhibition.

When comparing recall scores in Step 4 of the procedure illustrated in Figure 5 with appropriate control trials, inhibition of the comparison words presented in Step 1 is measured.
Figure 5. The negative priming technique for investigating inhibition of materials in the distractor activity of the complex-span paradigm. At Step 1, the participants alternate between a distractor activity (comparing the size of objects) and encoding to-be-recalled (TBR) words. At Step 2, they are requested to recall the assigned TBR words. At Step 3, they are presented with the words that were part of the distractor activity in Step 1, but this time they are targets for recall. At Step 4, they are requested to recall the items seen in Step 3.

Another promising way to carry on the work presented here is to investigate habituation towards auditory distraction (that is, the degree to which disruption reduces in magnitude as a function of increased exposure to the sound). It is quite clear that people are unable to habituate to the irrelevant sound effect (Ellermeier & Zimmer, 1997; Tremblay & Jones, 1998), whereas numerous studies have demonstrated habituation towards auditory deviants (e.g., Debener, Kranczioch, Herrmann, & Engel, 2002; Friedman, Cycowicz, & Gaeta, 2001; Sokolov, 1963). These observations are consistent with the duplex-mechanism account which suggests that the changing-state effect and the deviation effect are caused by qualitatively different mechanisms. One possibility is that people cannot habituate to the changing-state effect because it is caused by automatic perceptual processes, whereas they can habituate the deviation effect because it is can be overruled by cognitive-control processes.
and therefore modulated by individual differences in WMC. In light of this distinction, it
would be interesting to investigate if high-WMC individuals habituate to the deviation effect
at a faster pace than low-WMC individuals. This finding would provide further support for the
duplex-mechanism account of auditory distraction.

Potential applied implications

The negative consequences of noise for cognitive performance are nowhere as
serious as in schools and offices. Noise abatement interventions therefore have the largest
impact when applied to those environments. However, the resources are sparse and must be
applied economically. One way to meet this requirement is to give priority to individuals who
enjoy the largest effect of the interventions. As we have seen throughout this thesis, low-
WMC individuals are particularly susceptible to auditory distraction; especially to effects of
noise on tasks semantic in nature (e.g., reading comprehension, prose memory) and to
attentional capture from unexpected sounds. Since school- and office-related tasks usually are
language-based, and sounds with the potential to grab attention (e.g., slamming doors, phone
signals, moving chairs) are relatively common in those environments, low-WMC individuals
working here should suffer the most from noise. Based on this account, people with poor
WMC should be the first to receive actions against noise. Those individuals generally include
older adults (Salthouse & Babcock, 1991), young children (Gathercole, Pickering, Ambridge,
& Wearing, 2004) and those with poor scholastic achievement (Gathercole, Pickering, Knight,
& Stegmann, 2004).

Conclusion

Some authors have long since argued that processing of acoustic change in
sound streams is the reason why memory and cognition become distracted by irrelevant
sounds (e.g., Jones & Macken, 1993; Macken et al., 2009), but ten years ago it was not at all clear whether also cognitive control plays a role in this phenomenon. Based in large on studies reported in this thesis, it is by now quite clear that cognitive control capacities constitute a fundamental basis of individual differences in susceptibility to auditory distraction.

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References


Individual Differences in Susceptibility to the Effects of Speech on Reading Comprehension

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SUMMARY
Individuals with high working memory capacity (WMC) are less distracted by task-irrelevant speech than others. The mechanism behind this relationship, however, is not well understood, and it has only been found in a few paradigms. We used a Number updating task to measure WMC and two suppression mechanisms (immediate and delayed), and tested how they were associated with individual differences in susceptibility to the effects of speech on reading comprehension. The results revealed a negative relationship between WMC and susceptibility to speech distraction. Of the two suppression mechanisms, only immediate suppression was associated with speech distraction, suggesting that susceptibility to distraction is determined by the ability to immediately suppress the irrelevant speech. Furthermore, the relationship between WMC and speech distraction was mediated by the immediate suppression mechanism. The implications of these results and possible explanations of similar results found in other paradigms are discussed. Copyright © 2009 John Wiley & Sons, Ltd.

Reading without understanding would be little more than just looking at written words. To comprehend and remember what one reads is usually the very purpose of reading. This is not always easy to accomplish, especially not in the presence of background speech (Martin, Wogalter, & Forlano, 1988; Oswald, Tremblay, & Jones, 2000). Some of us, though, can become so focused on what we read that we do not even notice someone talking in the background. Recent research has begun to establish a greater understanding of the nature of these individual differences (Beaman, 2004; Boman, Enmarker, & Hygge, 2005; Elliott, Barrilleaux, & Cowan, 2006; Kjellberg, Ljung, & Hallman, 2008). However, there is still no comprehensive account of individual differences in susceptibility to the effects of speech on reading comprehension. The purpose of the present study was to address this issue.

According to the interference-by-process account of auditory distraction (e.g. Marsh, Hughes, & Jones, 2008), speech disrupts performance on tasks such as reading comprehension due to interference between two sets of processes: the semantic processes engaged in the primary task (e.g. reading) and non-deliberate processing of semantic information in speech. Individual differences in working memory capacity (WMC) seem to characterise how susceptible people are to this semantic interference (Beaman, 2004; see

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also Conway, Cowan, & Bunting, 2001). However, a relationship between WMC and susceptibility to effects of speech on semantic processes has, thus far, only been found with free recall of word-lists semantically related to the speech stream. Furthermore, several attempts have failed to find a similar relationship when participants perform tasks that rely heavily on seriation processes (e.g. Beaman, 2004; Elliott et al., 2006; Elliott & Cowan, 2005). These observations indicate that the relationship between WMC and susceptibility to speech distraction is not general in nature, and it would be most encouraging, from both a theoretical and an applied perspective, if this relationship could be demonstrated with some other task involving semantic processes such as reading comprehension.

Beaman’s (2004) findings can easily be explained by the WMC theory by Engle and colleagues (for a recent review, see Redick, Heitz, & Engle, 2008), according to which differences in WMC reflect differences in people’s ability to maintain control of task-relevant information, suppress task-irrelevant information and constrain attention to the primary task. The reason why WMC is related to speech distraction is, however, uncertain at present. Speech is automatically encoded, even if ignored (for a review, see Beaman, Bridges, & Scott, 2007), so it seems unlikely that individuals with high WMC are more able to simply ignore speech by constraining their attention. Another possibility is that they are more able to actively suppress encoded but non-target information so as to not interfere with the task goal.

Recent investigations into the working memory processes underlying reading comprehension have made use of a group of measures labelled ‘updating tasks’ (e.g. Carretti, Cornoldi, De Beni, & Romanò, 2005; Palladino, Cornoldi, De Beni, & Pazzaglia, 2001). The errors observed with these tasks are of interest here. Consider, for instance, the Number updating task developed by Carretti, Cornoldi, and Pelegrina (2007). In this task, sequences of 10 two-digit numbers are presented to the participants and the task goal is to recall the three smallest numbers. In principal, the first three numbers in the sequence must be held in memory (i.e. under attentional control). Then, when another number is presented that do not reach the recall criterion, that number must be processed (i.e. compared with numbers in memory), but then immediately suppressed. If, however, suppression is incomplete, those numbers may be recalled by mistake, which would result in an error labelled immediate intrusion (as it concerns items to be immediately suppressed). The set of processes involved in avoiding immediate intrusions are henceforth referred to as an immediate suppression mechanism. Reading while background speech is present resembles what participants must do when presented with a number to be immediately suppressed. That is, they must try to keep attentional control of information relevant for the task goal while suppressing interference from other materials. If immediate intrusions measure the mechanism required for suppressing speech while reading, the effects of speech on reading comprehension should be larger for participants who make immediate intrusion errors. Correct answers on the Number updating task should also be related to individual differences in susceptibility to speech distraction as they are measures of WMC, similar to correct answers on the well-known Operation span (OSPAN) task used by Beaman (2004). However, if the role of immediate suppression is important for this relationship, the relationship should be mediated by immediate intrusion errors.

Participants performing the Number updating task can also make another type of error labelled delayed intrusion. This error occurs when participant recall a number that once was appropriate for recall but should have been suppressed as lower numbers were presented later in the list. The set of processes involved in suppressing those items are henceforth referred to as a delayed suppression mechanism (as it concerns items to be
suppressed after being held in memory for a while). Delayed suppression is quite different from that of suppressing speech as it concerns proactive interference from items once held under attentional control, while irrelevant speech, by definition, is not held under attentional control before being suppressed. So, this mechanism should not be associated with disruption of reading comprehension per se. Yet, delayed suppression may still contribute to the effects of speech on reading comprehension in other ways. Several studies have found poor reading comprehenders to make more delayed intrusion errors than good comprehenders (Carretti et al., 2005; De Beni & Palladino, 2004; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998; Palladino et al., 2001). These findings suggest that efficient reading comprehension involves the ability to suppress no-longer relevant information. The effects of speech on reading comprehension may therefore, at least in part, be mediated by an effect of speech on the delayed suppression mechanism.

In the present study, participants performed the Number updating task and a reading comprehension task in a silent and an irrelevant speech condition. The main objective was to explore the relationship between individual differences in WMC, suppression mechanisms and susceptibility to the effects of irrelevant speech on reading comprehension. Specifically, the present study tested (1) whether the effects of irrelevant speech on reading comprehension is moderated by the immediate suppression mechanism (i.e. immediate intrusions made on the Number updating task in the silent condition), (2) whether the relationship between WMC (i.e. correct answers on the Number updating task in the silent condition) and susceptibility to speech distraction is mediated by the immediate suppression mechanism and (3) whether the effects of irrelevant speech on reading comprehension is mediated by an effect of irrelevant speech on delayed intrusions.

METHOD

Participants
A total of 40 persons (25 women) with a mean age of 23.70 (SD = 4.39) years participated in the experiment in exchange for a cinema ticket. All reported having normal or corrected-to-normal vision, normal hearing ability and normal reading skills.

Irrelevant speech sound
The irrelevant speech was recorded in an echo-free room. The speech consisted of a story about a fictitious culture, told by a male actor. The recording was downloaded into a computer and divided into 14 parts. Silent pauses between words and sentences were adjusted in order to maintain a fairly constant speech flow. The sound was played through headphones at approximately 70–75 dB (A).

Design and procedure
A within-subject design was used. The participants were seated alone in a silent room in front of a computer. They were asked to wear the headphones throughout the experiment, also when no sound was played, and they were instructed to ignore any sound they would hear in the headphones. Afterwards, they were asked if they had actually kept the headphones on the whole time and everyone acknowledged that they had. The participants
performed the tasks in two phases. First, they performed one Number updating task in the silent condition and another in the speech condition; and second, they performed one reading comprehension task in the silent condition and another in the speech condition. The order of the background conditions and the tasks was counterbalanced within the phases.

Tasks

Number updating task

This task was adopted from Carretti et al. (2007). Each of the two tasks consisted of 14 different lists with 10 two-digit numbers. The lists were presented in the centre of the computer screen with a 72-point font-size. Each list was preceded by the symbol ## which indicated to the participants where the numbers would be presented. Thereafter, the 10 numbers in the list were presented sequentially. The numbers were displayed for 2 seconds with an inter stimulus interval of 1 second.

The numbers in each list varied pseudo randomly between 15 and 99. The arithmetic distance between the lowest and the highest number within each list varied between 30 and 36. The difference between two arithmetically adjacent numbers within the list varied between 2 and 6. These restrictions were made because the arithmetic distance between within-list numbers has been found to affect performance (Carretti et al., 2007). The numbers to be recalled occurred only once within each task. Of the 14 lists, half required five updates and half required two updates (i.e. the number of times items in memory became no-longer relevant). The order of the lists within each test was the same for each participant and pseudo random. That is, the same list type was never presented more than twice in a row.

The participants began with reading an instruction for the task. They were told they should recall the three smallest numbers in the list in their order of presentation. They were instructed to guess if they had forgotten a number and make sure to place the numbers they remembered in the correct serial position. They were also given an example of a list and shown the correct recall for that list. The participants began with performing two practice trials, one of each list type, and then proceeded throughout the remaining 12 lists. A recall box appeared on the screen 2 seconds after the final number had been presented in the list. The participants typed their answer in the box and pressed a button allowing for the next list to be presented. When the task was performed in the speech condition, the irrelevant speech began playing 1 second before the symbol ## was presented and stopped 1 second before the recall box appeared on the screen. Each list was accompanied with 1 of the 14 parts of irrelevant speech. Each part was played only once within the test and the parts were presented in the same random order for each participant.

The responses were scored according to the following criteria. A correct answer was given to each of the three smallest numbers typed in the correct serial position. Hence, participants could get three correct answers per trial. Each number recalled that once was appropriate for recall, but should have been replaced by a lower number presented later in the list was scored as a delayed intrusion. An immediate intrusion was given to each number recalled that should have been immediately discarded because more appropriate numbers preceded them. Each of the three smallest numbers recalled in incorrect serial position was scored as an order error, and inventions were made when participants typed a number that had not been presented in the list.

Reading comprehension task

In previous studies into the effects of irrelevant speech on reading comprehension (Martin et al., 1988; Oswald et al., 2000), comprehension has been measured with questions...
administered after the participants have stopped reading the text. Such a test involves a long retention interval between reading and the testing of comprehension. With this task, it might be argued that speech disrupts long-term memory of the text rather than comprehension of it. Working memory (temporary storage and processing) is involved in comprehending the text, and if background speech has an immediate effect on semantic processes carried out by working memory, a test of comprehension that minimises the retention interval would probably capture disruption of these particular processes more efficiently. In the present study, both reading comprehension tasks consisted of 20 short texts. They were presented sequentially on the computer screen, each accompanied with a question and four alternative answers (of which one was correct). The participants were given 90 seconds to answer each question respectively. In the first five texts of each task, the question was written below the text and in order to answer the question, the participants had to draw conclusions from the meaning of the text and select one of the four alternative answers. In the remaining 15 texts of each task, a word was missing. The participant’s task was to select one of four words that should be placed at the position of the missing word in order to make the text coherent. Each of the four alternatives would make the phrase grammatically correct, but only one of them was accurate given the meaning of the text. Hence, with this task, the participants answered questions while having both the questions and the texts available when they replied. Before the participants began with the task, they were shown two text examples with questions and alternative answers. The participants responded by clicking on the computer keyboard. When an answer was given or if the participants failed to give an answer within the time limit, the next text was presented. When the test was performed in the irrelevant speech condition, the same 14 speech parts as those played during the updating task were played sequentially in the same random order for each participant throughout the test.

RESULTS

The reading comprehension task

The results on the reading comprehension task are summarised in Table 1. As can be seen in Table 1, irrelevant speech disrupted reading comprehension performance. This result did neither depend on the time taken to complete the task nor on the presentation order of conditions. A 2 (background conditions: speech vs. silence) × 2 (condition order: speech first vs. silence first) multivariate analysis of variance on reading comprehension scores and time taken to complete the test revealed a main effect of background conditions, $F(2, 37) = 3.38$, $\Lambda = .85$, $p < .05$, $\eta^2 = .15$, but no main effect of condition order.

Table 1. Number of correct answers and time taken on the reading comprehension task performed in the silent and in the speech condition collapsed on condition order

<table>
<thead>
<tr>
<th>Measure</th>
<th>Silence M</th>
<th>Silence SD</th>
<th>Speech M</th>
<th>Speech SD</th>
<th>F</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct answers</td>
<td>11.55</td>
<td>2.24</td>
<td>10.58</td>
<td>2.93</td>
<td>6.34*</td>
<td>.14</td>
</tr>
<tr>
<td>Minutes</td>
<td>14.22</td>
<td>3.00</td>
<td>14.41</td>
<td>2.56</td>
<td>&lt;1</td>
<td>&lt;.01</td>
</tr>
</tbody>
</table>

*p < .05.
$F(2, 37) = 1.17, \Lambda = .94, p = .30, \eta^2 = .06$, and no interaction between background conditions and condition order, $F(2, 37) = 1.98, \Lambda = .90, p = .15, \eta^2 = .09$. The univariate tests revealed that irrelevant speech disrupted reading comprehension, $F(1, 38) = 6.34, MSE = 2.99, p < .05, \eta^2 = .14$, but it did not affect the time taken to complete the task, $F < 1$. No further analyses were significant.

The Number updating task

Participants’ responses on the Number updating task are summarised in Table 2. As 17 out of 40 participants did no immediate intrusion error in the silent condition and 13 did none in the speech condition, these variables were dichotomised (i.e. no immediate intrusion error vs. at least one immediate intrusion error) before making the analyses. All analyses reported below, however, reached the same conclusions as control analyses using the raw score on immediate intrusions. As can be seen in Table 2, irrelevant speech reduced the number of correct answers and increased the number of inventions. Yet, these effects were qualified by interactions with condition order, occurring as a result of participants reporting more correct answers and fewer inventions in the silent condition when beginning in the irrelevant speech condition, but there was no difference between background conditions when they began in the silent condition. There was no effect of speech on the other types of responses. These conclusions are supported by a $\chi^2$ test which revealed no support for an effect of speech on immediate intrusion errors, $\chi^2(1, N = 40) = 0.11, p = .75$, and a 2 (background conditions: speech vs. silence) $\times$ 2 (condition order: speech first vs. silence first) multivariate analysis of variance on correct answers, order errors, inventions and delayed intrusions. The multivariate tests revealed a main effect of background condition, $F(4, 35) = 6.25, \Lambda = .58, p < .01, \eta^2 = .42$. There was no main effect of condition order, $F(4, 35) = 1.24, \Lambda = .88, p = .31, \eta^2 = .12$, but the interaction between background condition and condition order almost reached significance, $F(4, 35) = 2.56, \Lambda = .77, p = .056, \eta^2 = .23$. The univariate tests revealed a main effect of background condition on the number of correct answers, $F(1, 38) = 10.52, MSE = 11.64, p < .01, \eta^2 = .22$, which interacted with condition order, $F(1, 38) = 10.52, MSE = 11.64, p < .01, \eta^2 = .22$ and a main effect of background condition on inventions, $F(1, 38) = 14.77, MSE = 7.64, p < .01, \eta^2 = .28$, which also interacted with condition order, $F(1, 38) = 4.26, MSE = 7.64, p < .05, \eta^2 = .10$. No further analyses were significant. As irrelevant speech did not increase the number of delayed intrusions committed, there was no support for the assumption that the

<table>
<thead>
<tr>
<th>Response</th>
<th>Silence</th>
<th>Speech</th>
<th>F</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M$</td>
<td>SD</td>
<td>$M$</td>
<td>SD</td>
</tr>
<tr>
<td>Correct answers</td>
<td>21.43</td>
<td>5.45</td>
<td>18.95</td>
<td>6.56</td>
</tr>
<tr>
<td>Inventions</td>
<td>6.80</td>
<td>2.70</td>
<td>9.18</td>
<td>4.41</td>
</tr>
<tr>
<td>Order errors</td>
<td>3.95</td>
<td>3.53</td>
<td>4.03</td>
<td>3.07</td>
</tr>
<tr>
<td>Delayed intrusions</td>
<td>2.40</td>
<td>1.82</td>
<td>2.63</td>
<td>2.29</td>
</tr>
<tr>
<td>Immediate intrusions*</td>
<td>1.40</td>
<td>1.57</td>
<td>1.28</td>
<td>1.19</td>
</tr>
</tbody>
</table>

**$p < .01$.**  
*No analysis of variance was performed on immediate intrusions.*
effects of irrelevant speech on reading comprehension is mediated by an effect of speech on the delayed suppression mechanism (Judd, Kenny, & McClelland, 2001).

Susceptibility to effects of speech on reading comprehension

In order to investigate the relationships between the responses on the Number updating task and the effects of irrelevant speech on reading comprehension, residual analyses were calculated. This is to be preferred to simple difference scores between reading comprehension in the silent and in the speech condition (Cronbach & Furby, 1970; Zumbo, 1999). However, consistent results were found with control analyses based on difference scores. In the residual analyses below, the effect of speech on reading comprehension is revealed by the residual variance withheld after partialing out the variance explained by reading comprehension in the silent condition from reading comprehension in the speech condition. If some variable (say immediate intrusions) explains a significant part of this residual variance, then the background condition variable interacts with (is moderated by) this variable.

First, the hypothesis that people with a poor immediate suppression mechanism are more distracted by speech was tested with a hierarchal regression analysis. Reading comprehension in the speech condition was selected as dependent variable, reading comprehension in the silent condition and condition order were selected as independent variables in the first step, and immediate intrusions made in the silent condition (dichotomised) was selected as independent variable in the second step. For validity, both measures of delayed suppression and the measure of immediate suppression in the speech condition (dichotomised) were also added in the second step. The regression model was significant, $R^2 = .75$, $F(4, 35) = 6.84$, MSE = 4.51, $p < .01$. Both reading comprehension in the silent condition, $\beta = .52$, $t = 4.16$, $p < .01$ (in the second step), and immediate intrusions in the silent condition, $\beta = -.49$, $t = -3.55$, $p < .01$, explained a significant part of the variance, but the other variables did not. These results indicate that the effect of irrelevant speech on reading comprehension was larger for participants with a poor immediate suppression mechanism. The delayed suppression mechanism, however, was not associated with this effect and the impact of speech on immediate and delayed suppression did not contribute with a unique explanation of the variance.

Second, the hypothesis that an immediate suppression mechanism (i.e. immediate intrusions in the silent condition) mediates the relationship between WMC (i.e. correct answers on the Number updating task in the silent condition) and the effects of speech on reading comprehension was tested. This testing follows the mediation analyses described by Baron and Kenny (1986) and by Frazier, Tix, and Barron (2004). First, if this hypothesis should be confirmed, correct answers on the Number updating task must, of course, moderate the effect of speech on reading comprehension. A new hierarchal regression analysis was calculated with the same dependent variable and the same independent variables in the first step as those in the regression analysis above, but with correct answers on the Number updating task in the silent condition and, for completeness, in the speech condition as independent variables in the second step. This analysis revealed that correct answers on the Number updating task in the silent condition explained a significant part of unique variance, $\beta = .36$, $t = 2.08$, $p < .05$, while those in the speech condition did not, $\beta = -.05$, $t = -0.27$, $p = .79$. Hence, the first criterion for mediation was reached; the effect of speech on reading comprehension was larger for participants with low WMC. The effect of speech on the Number updating task, however, did not provide any additional.
explanation of the variance. Second, if immediate intrusions mediate the relationship between WMC and susceptibility to speech distraction, there must be a significant correlation between correct answers and immediate intrusion errors (in the silent condition). Indeed, this correlation was significant, \( r(38) = -.82, p < .01 \). Finally, the interaction between correct answers and background conditions must disappear when immediate intrusions are added to the regression model. This criterion was also reached. When immediate intrusions made in the silent condition (dichotomised) was added as an independent variable in a third step of the hierarchical regression analysis, the variance explained by correct answers in the silent condition was no longer significant, \( \beta = -.02, t = -0.09, p = .93 \), while the variance explained by immediate intrusions still reached significance, \( \beta = -.43, t = -2.05, p < .05 \). Furthermore, the reduction in variance explained by correct answers was significant, \( z = 1.99, p < .05 \). Taken together, the analyses support the hypothesis that an immediate suppression mechanism mediates the relationship between WMC and the effects of speech on reading comprehension.

**DISCUSSION**

This study aimed to explore individual differences in susceptibility to disruption of reading comprehension by irrelevant speech. The experiment revealed four major findings. First, irrelevant speech disrupted reading comprehension; second, the disruption was larger for people with a poor immediate suppression mechanism; third, the disruption was also associated with WMC as measured by correct answers on the Number updating task and forth, this relationship was mediated by the immediate suppression mechanism. The effects of irrelevant speech on reading comprehension were not mediated by an effect of speech on the delayed suppression mechanism.

The results reported here are, to our knowledge, the first to demonstrate a relationship between WMC and susceptibility to the effects of speech on reading comprehension. This finding is well in line with the results reported by Beaman (2004) and establishes a relationship between WMC and susceptibility to speech distraction beyond free recall of short word-lists. Since WMC seems not negatively related to the effects of speech on seriation processes (e.g. Elliott et al., 2006; Elliott & Cowan, 2005), but the results reported here and by Beaman (2004) show that WMC is associated with effects of speech on semantic processes, the mechanisms underlying individual differences in susceptibility to those effects seem qualitatively different. Future research should be directed towards the interactions between specific processes rather than looking at people’s general ability to avoid interference from distracting sounds.

Traditional measures of WMC, such as OSPAN used by Beaman (2004), are characterised by simultaneous processing and storage. As these tasks, by definition, require the engagement of several cognitive mechanisms, it’s intrinsically difficult to determine why WMC is related to people’s ability to avoid speech distraction. However, as the present investigation used the Number updating task while Beaman (2004) used OSPAN, it seems as if they both measure a mechanism underlying this relationship. When trying to pinpoint this mechanism, it might be useful to address the components contributing to people’s performance on OSPAN. In the common version of the task, participants are presented with sets of operation-word strings (e.g. \( IS (3 \times 2) + 6 = 12? \) CACTUS). To each string, participants should respond ‘yes’ or ‘no’ to indicate if the mathematical expression is true or not and remember the word. After being presented with two to six strings, participants
are to recall the words in order of presentation. Efficient performance on this task involves mechanisms very similar to those involved in the Number updating task. First, participants must be able to keep attentional control of the to-be-recalled words held in memory while responding to the mental calculations, and suppress interference from the mathematical expressions since they may otherwise interfere with the target-items (i.e. immediate suppression). Second, after each trial, participants must suppress words that once were, but are no longer, relevant for recall so as to avoid proactive interference (i.e. delayed suppression). The contribution from delayed suppression to performance on OSPAN may be the reason why this task predicts people’s ability to suppress proactive interference on, for example, the paired-associates task (Rosen & Engle, 1998). In fact, as a demonstration of how important delayed suppression is to the predictive power of WMC measures, Lustig, May, and Hasher (2001) found it to be completely responsible for the well-established relationship between performance on working memory span tasks and reading comprehension. We argue that the contribution from the other mechanism, immediate suppression, is what underlies the relationship between people’s performance on a WMC measure and their susceptibility to speech distraction. In support for this claim, the results reported here show that the effects of irrelevant speech on reading comprehension are larger for participants who make immediate intrusion errors in the Number updating task. Furthermore, the relationship between WMC, as measured by correct answers on the Number updating task, and the effects of speech on reading comprehension was mediated by immediate intrusion errors. It should be noted that we do not argue that the immediate suppression mechanism is separate from WMC as usually measured with other tasks. The mechanism is rather a part of that construct and responsible for the ability to avoid interference from unattended speech.

In summary, individual differences in susceptibility to the effects of speech on semantic processes have been a research topic largely ignored. However, recent advances by Beaman and others have provided a new platform for research on this topic, which will help us to understand the mechanisms underlying these differences. From the present investigation, we learned that a relationship between WMC and the disruptive effects of speech can be found for reading comprehension, and that people with low WMC are those most in need of a quiet reading environment, providing obvious suggestions to schools, open-offices landscapes and other work environments where reading takes place in the presence of background speech.

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A sub-process view of working memory capacity: Evidence from effects of speech on prose memory

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In this article we outline a “sub-process view” of working memory capacity (WMC). This view suggests that any relationship between WMC and another construct (e.g., reading comprehension) is actually a relationship with a specific part of the WMC construct. The parts, called sub-processes, are functionally distinct and can be measured by intrusion errors in WMC tasks. Since the sub-processes are functionally distinct, some sub-process may be related to a certain phenomenon, whereas another sub-process is related to other phenomena. In two experiments we show that a sub-process (measured by immediate/current-list intrusions) is related to the effects of speech on prose memory (semantic auditory distraction), whereas another sub-process (measured by delayed/prior-list intrusions), known for its contribution to reading comprehension, is not. In Experiment 2 we developed a new WMC task called “size-comparison span” and found that the relationship between WMC and semantic auditory distraction is actually a relationship with a sub-process measured by current-list intrusions in our new task.

Keywords: Semantic auditory distraction; Size-comparison span; Sub-process view; Working memory capacity.

For a long time, cognitive psychology and neuroscience have debated why working memory capacity (WMC) is such a successful correlative instrument (for a review, see Engle, 2002). Some researchers have suggested that WMC measures attentional control in the presence of interference (e.g., Engle, Tuholski, Laughlin, & Conway, 1999; Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2003), whereas others have proposed that WMC measures inhibition (Hasher & Zacks, 1988; Lustig, Hasher, & Zacks, 2008) or that it merely measures mental storage capacity (Cowan, 2001, 2005). These views differ in detail, but they all suggest that WMC reflects a single unitary construct. Moreover, since this construct (i.e., attention or inhibition) is involved in most, if not all, cognitive tasks, it is easy to see why WMC correlates with nearly everything. However, recent theoretical developments by Unsworth and Engle (2007b) indicate that WMC is no unitary construct. They showed that retrieval of items from primary memory (i.e., items within attention) and retrieval of items from secondary memory (i.e., long-term memory) explain unique
variance in a traditional WMC task (i.e., operation span). Based on this finding the authors concluded that “WMC is not a unitary function, but rather represents a conglomeration of separate abilities” (Unsworth & Engle, 2007b, p. 116). The purpose of the present article is to show that at least some of those abilities are functionally distinct: some are responsible for the relationship between WMC and reading comprehension, whereas others are responsible for the relationship between WMC and the disruption of prose memory by background speech.

WORKING MEMORY CAPACITY AND ITS RELATION TO SEMANTIC AUDITORY DISTRACTION AND READING COMPREHENSION

Tasks that require semantic processing (e.g., reading comprehension) are particularly disrupted by the meaning of background speech (Bell, Buchner, & Mund, 2008; Jones, Miles, & Page, 1990; Martin, Wogalter, & Forlano, 1988; Oswald, Tremblay, & Jones, 2000). This type of disruption is called “semantic auditory distraction”. Marsh, Hughes, and Jones (2008, 2009) have suggested that semantic auditory distraction occurs because people fail to monitor appropriately the source of to-be-ignored background speech. These findings agree with Beaman’s work (2004). Beaman presented participants with lists of visual to-be-remembered words (e.g., fruits), then with lists of to-be-ignored speech words that are semantically related to the to-be-remembered words (e.g., other fruits). The participants were then asked to recall the to-be-remembered words. The findings revealed that low-WMC individuals recalled more of the to-be-ignored speech words than did high-WMC individuals. Beaman suggested that individual differences in WMC reflect differences in a “source-monitoring” ability (Johnson, Hashtroudi, & Lindsay, 1993), which is the reason why WMC predicts people’s tendency to mistakenly recall words with the wrong source (i.e., the auditorily presented words instead of the visually presented words).

In a recent experiment Söörqvist, Halin, and Hygge (2010) aimed to extend Beaman’s (2004) findings about semantic auditory distraction to reading comprehension, and to specify the relationship between WMC and semantic auditory distraction in greater detail. To this end, the authors used the number-updating task (Carretti, Cornoldi, & Pelegrina, 2007) as a measure of WMC (see Figure 1 for an illustration of the task). In the number-updating task, sequences of 10 two-digit numbers (e.g., 23, 47, 58, 49, 63, 30, 52, 41, 67, 45) are presented to the participants. The task is to recall the three lowest numbers in the list (e.g., 23, 30, 41). In principle the three numbers presented first must be maintained in working memory (e.g., 23, 47, 58). When a number higher than the three in the memory set is presented (e.g., 63), that number must be encoded and processed (i.e., compared with the highest number held in memory), but then immediately discarded so as not to be confused with the to-be-recalled items. If participants fail to do so they may substitute the numbers in the

<table>
<thead>
<tr>
<th>List of numbers presented sequentially</th>
<th>Required cognitive mechanism</th>
<th>Currently correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>Store “23”</td>
<td>“23”</td>
</tr>
<tr>
<td>47</td>
<td>Store “47”</td>
<td>“23 47”</td>
</tr>
<tr>
<td>58</td>
<td>Store “58”</td>
<td>“23 47 58”</td>
</tr>
<tr>
<td>49</td>
<td>Delete “58”</td>
<td>“23 47 49”</td>
</tr>
<tr>
<td>63</td>
<td>Exclude “63”</td>
<td>“23 47 50”</td>
</tr>
<tr>
<td>50</td>
<td>Delete “49”</td>
<td>“23 47 50”</td>
</tr>
<tr>
<td>52</td>
<td>Exclude “52”</td>
<td>“23 47 30”</td>
</tr>
<tr>
<td>41</td>
<td>Delete “47”</td>
<td>“23 30 41”</td>
</tr>
<tr>
<td>67</td>
<td>Exclude “67”</td>
<td>“23 30 41”</td>
</tr>
<tr>
<td>45</td>
<td>Exclude “45”</td>
<td>“23 30 41”</td>
</tr>
<tr>
<td>Correct</td>
<td>Example</td>
<td>Outcome</td>
</tr>
<tr>
<td>23</td>
<td>“23”</td>
<td>Correct</td>
</tr>
<tr>
<td>30</td>
<td>“30”</td>
<td>Immediate intrusion</td>
</tr>
<tr>
<td>41</td>
<td>“41”</td>
<td>Delayed intrusion</td>
</tr>
</tbody>
</table>

Figure 1. The number-updating task. Lists of 10 two-digit numbers are presented to the participants. The task is to recall the three lowest numbers after list presentation. During presentation the participants must “exclude” numbers larger than the three lowest presented so far in the list (e.g., 63), and “delete” numbers that become outdated when they are no longer one of the three lowest numbers presented (e.g., 58). If the participants recall a number that should have been “excluded”, this is scored as an “immediate intrusion”. If the participants recall a number that should have been “deleted”, this is scored as a “delayed intrusion”.

A SUB-PROCESS VIEW OF WMC
memory set and later recall a number too large to reach the criterion for recall. This type of error is labelled an “immediate intrusion” because it concerns items to be immediately excluded from the memory set. Importantly, immediate intrusions are intrusions from items that are part of the task but never meant for recall. When the participants are presented with a number higher than the three held in memory, they must keep this to-be-excluded item apart from the memory set. This situation resembles what the participants must do in Beamam’s (2004) short-term memory experiment when they are presented with a list of to-be-ignored speech words while holding another list of to-be-recalled words in memory. That is, in both cases the participants must distinctly maintain to-be-recalled items and avoid confusion with other, potentially relevant but ultimately irrelevant, items.

Based on the findings reported by Beamam (2004), Sörqvist et al. (2010) expected that immediate intrusion errors in the number-updating task correlate with the effects of speech on reading comprehension. The results supported this hypothesis. The participants who made immediate intrusion errors in the updating task were the ones most susceptible to the effects of speech on reading comprehension. Furthermore, the task score (i.e., correct answers on the number updating task) also predicted the magnitude of disruption (demonstrating a relationship between WMC and semantic auditory distraction). However, further analyses revealed that this relationship completely disappeared when immediate intrusions were statistically controlled for, whereas immediate intrusions still explained the differences in susceptibility to distraction. The keypoint of this finding is that some specific mechanism, measured by immediate intrusions, seems to underlie the relationship between WMC and semantic auditory distraction. Therefore, WMC is no unitary construct, there are several assumptions that underlie the sub-process view. A task that measures WMC requires, by definition, the execution of several processes (for a review of those tasks, see Conway et al., 2005). Therefore, WMC is no unitary construct, but a set of several sub-processes. This can be described by the quasi-mathematical formula “WMC = sub-process1 + sub-process2 + . . . + sub-processn”. As a consequence, a measure of WMC can be related to other constructs for different reasons. For instance, WMC can correlate with some construct A (e.g., semantic auditory distraction) only because the task used to measure WMC (e.g., number updating) requires the action of a
critical sub-process (e.g., an inclusion/exclusion mechanism) that is also required by the task used to measure construct A; whereas WMC can correlate with some other construct B (e.g., reading comprehension) because another sub-process (e.g., a deletion/suppression mechanism) is required both by the WMC task and by the task used to measure construct B. The first point of this perspective is that any relationship between WMC and another phenomenon is actually one between individual and measurable sub-processes and that other phenomenon. In other words, the WMC concept per se is entirely unnecessary in explaining individual differences in cognitive functioning. The second point of the sub-process view is that individual sub-processes covered by the WMC construct are functionally distinct. Importantly, different types of responses in WMC tasks have different correlative properties because they measure functionally distinct sub-processes. For instance, delayed intrusions in the number-updating task are related to reading comprehension, whereas immediate intrusions are not. In addition, immediate intrusions are related to semantic auditory distraction, whereas delayed intrusions are not. That is, the delayed and immediate intrusion errors measure distinct sub-processes.

The third point advocated by the sub-process view is a methodological one: the statistical correlation between WMC task scores (e.g., correct answers on number updating) and another task score (e.g., reading comprehension score) disappears when critical error responses are statistically controlled for (e.g., delayed intrusions), because it is the sub-process tapped by the errors that is actually related to the other task score. Furthermore, since this sub-process is included in the sum of sub-processes that constitutes the WMC construct, it causes the relationship between the WMC task score and the other task score.

Note that the sub-process view is not a theory that intends to explain the nature of the sub-processes covered by the WMC construct. What is measured by different responses in WMC tasks must be subjected to empirical work and additional theory. The sub-process view is rather a framework for how correlations can be investigated and understood. We suggest that a single explanation cannot account for why WMC is related to other constructs. In other words, differences in WMC do not merely reflect differences in attentional control (e.g., Kane & Engle, 2003) or mental storage capacity (Cowan, 2005) or an inhibition mechanism (e.g., Lustig et al., 2008). The reason why WMC is related to some construct is not the same as the reason why it is related to others. Because of this complex relationship, it is impossible to pinpoint the nature of WMC by correlating it with other constructs. To understand the nature of WMC researchers are forced to measure different parts of the WMC construct and specify how the parts relate to other constructs.

Since Unsworth and Engle (2007b) have made similar attempts to divide the WMC construct into smaller units (i.e., primary and secondary memory), the differences between their view and the sub-process view should be clarified. In particular, they argue that low-WMC individuals suffer from an inefficient search of items in secondary memory (Unsworth & Engle, 2006a, 2006b) as evidenced by low-WMC individuals making more prior-list intrusion errors (i.e., recalling items that were relevant for recall on previous trials, but are not relevant on the present trial) when undertaking memory tasks (Unsworth, 2007). Differences in this ability may explain why WMC is related to higher-order cognition; however, retrieval of items from primary memory has little if any consequences for the correlative properties of WMC (Unsworth & Engle, 2007b). The view we endorse is similar to Unsworth and Engle’s view in the sense that WMC is non-unitary, yet the two perspectives differ regarding how and why WMC is related to other phenomena. According to the sub-process view, WMC task scores correlate with other task scores because the participants are required to use the same cognitive process when they undertake the tasks used to measure WMC and that other phenomenon. This can be any process, including retrieval from secondary memory. Hence, the sub-process view and Unsworth and Engle’s view complement rather than oppose one another. The sub-process view assumes that WMC may be related to reading comprehension because retrieval from secondary memory is necessary when performing WMC and reading comprehension tasks, but WMC is related to semantic auditory distraction for intrinsically different reasons.

**EXPERIMENT 1**

Sörqvist et al. (2010) measured reading comprehension by requesting participants to answer questions about the meaning of a written text,
with the text available for review when answering the questions. Hence, the participants did not have to retain the text materials for later recall. Experiment 1 aimed to test if the relationship found in Sörgqvist et al.’s study between immediate intrusions in the number-updating task and effects of speech on reading comprehension can be extended to the effects of speech on prose memory. To this end, we used a prose memory task which requires that participants retain the text materials for later recall. Since this task is known to be more vulnerable to speech than to non-speech sounds (Sörgqvist, in press), this type of task seems particularly appropriate for testing semantic interference caused by speech. Experiment 1 also aimed to show that immediate intrusions are more strongly related to semantic auditory distraction than delayed intrusions are, which would support the assumption that immediate and delayed intrusions measure functionally distinct sub-processes.

Method

Participants

A total of 24 people (14 women) with a mean age of 21.96 (SD = 2.44) years participated in Experiment 1 in exchange for a cinema ticket. All were native Swedish speakers, and reported normal or corrected-to-normal vision, normal hearing, and normal reading skills. This study has been reviewed and approved by the local research ethics committee.

Irrelevant speech

The irrelevant speech was recorded in an echo-free room. The speech consisted of a story about a fictitious culture called “the Ansarians” told by a male actor. The recording was downloaded into a computer and divided into 10 segments. Silent pauses between words and sentences were adjusted in order to maintain a fairly constant flow of words. The sound was played back through headphones at approximately 65 dB(A).

Tasks

Number updating. This task was adopted from Carretti et al. (2007). The task involved 18 different lists. Each list consisted of 10 two-digit numbers varying pseudo-randomly between 15 and 99. If the numbers within a list were arranged in arithmetic order, the difference between two adjacent numbers varied between 2 and 6, and the arithmetic distance between the lowest and the highest number within the lists varied between 30 and 36. The lists were designed so as to require five, three, and one update (i.e., exchange of numbers held in memory) respectively. There were six lists of each type ordered into blocks with one of each type in each block. The blocks and the lists within blocks were presented in the same random order for each participant. The first block was considered practice and removed from the analyses. At presentation, the numbers were displayed in the centre of a computer screen. Each list was preceded by the symbol ## to indicate that a new list was about to begin. Thereafter, the 10 numbers in the list were presented sequentially with a display time of 2 seconds and an interstimulus interval of 2 seconds. A recall box appeared on the screen 1 second after the final number in the list had been presented. The participants typed their answer in the box and then pressed a button allowing the next trial to begin.

The participants began by reading instructions for the task. They were told to recall the three smallest numbers in the list in their order of presentation. If they could not recall a number, they were to guess. If they could recall a number (without guessing), they placed the number in the correct serial position. They were also given an example of a list and shown the correct recall for that list. The responses were scored according to the following criteria. A correct answer was given to each one of the three smallest list numbers that were recalled in the correct serial position. Immediate intrusions were made when the participants recalled numbers that should have been immediately discarded because more appropriate numbers preceded them, and delayed intrusions were made when the participants recalled numbers that once were appropriate for recall, but should have been replaced by lower numbers presented later in the list.

Prose memory. In order to counterbalance background conditions between participants, two prose memory tasks were developed. Each task consisted of 10 short paragraphs. In one task the paragraphs told the story of a fictitious culture called “the Timads”, and in the other task the paragraphs told the story of another fictitious culture called “the Lobiks”. Before initiating the task participants read an instruction informing them to read the paragraphs thoroughly to
comprehend fully, and to remember them as they were to be asked questions on the contents later on. The tasks consisted of two phases: one reading phase and one recall phase. In the first phase the paragraphs were presented sequentially on the computer screen. Each paragraph was displayed for 1 minute. After each paragraph, but before the next was presented, the participants were asked if they had managed to read the entire paragraph. In the second phase of the task the participants were asked to answer 20 recall questions about facts explicitly stated in the paragraphs (e.g., “What did the messenger do to upset the dynast-king?”). Answers were never longer than a single sentence (e.g., “He refused to bow”) and scored as correct if they contained specific keywords (e.g., “refused and bow”) or described the relevant meaning of the keywords (e.g., “He did not want to bow”). The questions were presented sequentially by the computer and responses were given by typing on the computer keyboard. The first two questions concerned the first paragraph presented during the reading phase; the third and fourth question concerned the second paragraph, and so on. When performing the task with background speech, each paragraph was accompanied with one of the speech segments, but all questions were presented and answered in silence. Irrelevant speech was presented this way to restrict its effects to processes engaged when reading. The participants were instructed to ignore any sound they might hear and were assured they would not be asked questions about its content.

Design and procedure

A within-participants design was used. The participants sat alone in a silent room in front of the computer. They were asked to wear the headphones throughout the experiment, even if no sound was played. Afterwards they were asked if they had complied with this requirement and everyone acknowledged that they had. The participants began by performing the updating task. Next they performed the prose memory tasks in two phases. First they performed one of the tasks either in the silent condition or in the irrelevant speech condition. Second, they performed the other task: this time in the irrelevant speech condition if the first one was performed in the silent or vice versa. The order of the two background conditions (speech vs silence) and the two prose memory tasks was counterbalanced between participants. The entire experimental session lasted for about 60 minutes.

Results

Prose memory

A total of five paragraphs (1%) were reported as not completely read. Therefore the results from the prose memory task were scored as a proportion of paragraphs completely read. Recall was lower for texts read with background speech in comparison with recall for texts read in silence (Table 1). A 2 (background condition: silence vs. speech) × 2 (condition order: silence first vs speech first) analysis of variance revealed a substantial and significant difference between the background conditions, $F(1, 22) = 22.84$, $MSE = 0.03$, $p < .01$, $\eta^2 = .51$. Neither a main effect of condition order nor an interaction between condition order and background condition were noted in the analysis, both $F < 1$.

The relationship between working memory capacity and semantic auditory distraction

Residual analyses were used to investigate the mechanisms behind individual differences in susceptibility to the effects of irrelevant speech on prose memory. This procedure should be preferred to simple difference scores between conditions (e.g., Cronbach & Furby, 1970). In the residual analyses below, the individual differences in susceptibility to the effect of speech on prose memory are revealed by the residual variance left when the variance explained by prose memory in the silent condition were removed from prose memory in the speech condition. If some variable explains a significant part of this residual variance, this variable predicts the participants’ susceptibility to the effect of speech on prose memory. For instance, a negative relationship between immediate intrusions and this residual variance would indicate that people who make many immediate intrusion errors are more distracted by speech than are individuals who make few immediate intrusion errors.

To recapitulate, the sub-process view advocated here suggests that WMC consists of several sub-processes, some of which may be related to semantic auditory distraction whereas others are not. Two analyses were made to test this hypothesis. First, the relationship between immediate intrusions and semantic auditory distraction and between delayed intrusions and semantic
auditory distraction were analysed in separate regression models. Second, to examine whether the two types of intrusions errors contributed to semantic auditory distraction, we simultaneously put them into a regression model (Table 2). We hypothesised that immediate intrusions, but not delayed intrusions, would explain a unique variance. The sub-process view also suggests that the score on the number-updating task (i.e., correct answers) should be related to semantic auditory distraction, but this relationship should disappear when the critical sub-process (i.e., immediate intrusion errors) is statistically controlled for. Two analyses were made to test these assumptions. First, the relationship between the score on the number updating task and semantic auditory distraction was tested in a separate regression analysis. Second, the contribution from the task score and the immediate intrusions were entered simultaneously into a regression model (Table 2).

The number-updating task was scored in terms of correct answers (M = 30.33, SD = 8.23; range 14–43), immediate intrusions (M = 1.79, SD = 2.11; range 0–8), and delayed intrusions (M = 1.88, SD = 1.42; range 0–4). The correlation between immediate and delayed intrusions was non-significant, r(22) = .17, p = .45. First, the contribution from immediate and delayed intrusions to the effects of speech on prose memory was investigated. A hierarchical regression analysis was carried out with prose memory in the speech condition as a dependent variable, prose memory in the silent condition and condition order as independent variables in the first step, immediate intrusion errors as independent variable in the second step, and delayed intrusions as independent variable in the third step. The regression model was significant in all steps, R² = .65, F(2, 21) = 19.53, MSE = 0.01, p < .01 (in the first step). Prose memory in the silent condition explained a significant part of the variance, β = .81, t = 6.23, p < .01 (in the first step), whereas condition order did not, β = .06, t = 0.44, p = .67 (in the first step). Adding immediate intrusion errors to the regression model in the second step explained another significant part of the variance.

### Table 1
Scores on the prose memory task as proportions of paragraphs completely read

<table>
<thead>
<tr>
<th>Prose memory</th>
<th>Silence</th>
<th>M</th>
<th>SD</th>
<th>Speech</th>
<th>M</th>
<th>SD</th>
<th>Difference</th>
<th>M</th>
<th>SD</th>
<th>F</th>
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</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td>.61</td>
<td>.17</td>
<td>.49</td>
<td>.19</td>
<td>.11</td>
<td>.11</td>
<td>22.84**</td>
<td>.51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 2</td>
<td>.54</td>
<td>.15</td>
<td>.47</td>
<td>.17</td>
<td>.07</td>
<td>.12</td>
<td>12.25**</td>
<td>.23</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The F-values are based on within-participants designs.

** p < .01.

### Table 2
Hierarchical regression analyses of the relation of individual measures from the number-updating task to the effects of speech on prose memory in Experiment 1

<table>
<thead>
<tr>
<th>Measure</th>
<th>Relation to prose memory disruption</th>
<th>β</th>
<th>t</th>
<th>ΔR²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predictors entered alone</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immediate intrusions</td>
<td>−.27</td>
<td>−2.21*</td>
<td>.07</td>
<td></td>
</tr>
<tr>
<td>Number updating score</td>
<td>.26</td>
<td>2.10*</td>
<td>.06</td>
<td></td>
</tr>
<tr>
<td>Predictors entered simultaneously</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immediate intrusions</td>
<td>−.27</td>
<td>−2.14*</td>
<td>.07</td>
<td></td>
</tr>
<tr>
<td>Number updating score</td>
<td>.01</td>
<td>0.11</td>
<td>&lt;.01</td>
<td></td>
</tr>
<tr>
<td>Predictors entered simultaneously</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immediate intrusions</td>
<td>−.17</td>
<td>−1.06</td>
<td>.02</td>
<td></td>
</tr>
<tr>
<td>Number updating score</td>
<td>.14</td>
<td>.85</td>
<td>.01</td>
<td></td>
</tr>
</tbody>
</table>

* p < .05.

* Standardised regression coefficient for predictors of prose memory in the irrelevant speech condition after control for prose memory in the silent condition and condition order.
Discussion

The results from Experiment 1 indicate (a) people who are susceptible to immediate intrusions in the number-updating task are more susceptible to the effects of speech on prose memory than are people not susceptible to immediate intrusions, (b) that correct answers in the number-updating task is also related to this kind of disruption, but this relationship disappears when immediate intrusions are statistically controlled for, and (c) that delayed intrusions are not related to semantic auditory distraction.

The results support the sub-process view of WMC in that a specific and measurable part of the WMC construct (i.e., a sub-process) is related to distraction, whereas another part of the WMC construct (i.e., another sub-process) is not related to distraction. However, Sörgqvist et al. (2010) found that the relationship between correct answers on the updating task and semantic auditory distraction was eliminated when immediate intrusions were taken into account and the contribution of immediate intrusion errors remained significant.

The number-updating task is compromised by a few problems that may have limited the validity of the results reported in Sörgqvist et al. (2010) and in Experiment 1. For instance, when scoring responses in the task it is difficult to separate intrusions from previous trials (i.e., prior-list intrusions) from intrusions from the current trial (i.e., immediate and delayed intrusions) because the same item is presented on several trials. Moreover, when a number is presented to the participant there is no cue telling the participant what to do with the number. Instead, whether or not the number should be included in the memory set depends on the numbers the participants supposedly are holding in memory. If participants forget numbers presented early in the list, they will be unable to make an accurate judgement of the successive numbers. Therefore they may decide to maintain a number for recall because they have forgotten earlier list numbers, not because failure due to the inclusion/exclusion mechanism. Similarly, since the participants were instructed to guess if they did not know the accurate numbers, an immediate or delayed intrusion could be the result of guessing rather than failed gating mechanisms. Hence, although the number-updating task is a good measure for several purposes, it is not particularly well suited
for measuring the processes of interest here. To solve these problems we developed a new task called “size-comparison span” (SICSPAN).

In SICSPAN, sets of size-comparison word pairs (e.g., cow and cat) are presented to the participants (Figure 2). The participants’ task is to answer a question about the relative size of the objects (e.g., Is COW larger than CAT?). After answering the question, a third word is presented (e.g., CROCODILE). The participants are instructed to maintain this third word in memory for later recall. When the to-be-remembered word has been presented, another size-comparison pair is presented or the list ends depending on the list length. When the final to-be-remembered word has been presented, the participants are probed to recall. At recall, the participants must spontaneously recall words presented in the size-comparison part of the task within the same list. This is labelled a “current-list intrusion”. Critically, current-list intrusions in SICSPAN are intrusions from items never meant for recall. This is conceptually equivalent to the immediate intrusions in the number-updating task and as such should measure the same mechanism. That is, the participants must exclude the words presented during the size-comparison part of the task from the memory set by adapting an inclusion/exclusion mechanism. Therefore, we expected individual differences in susceptibility to current-list intrusions to be related to semantic auditory distraction.

SICSPAN has several advantages over the number-updating task. First, each item is only presented once during the test, so when scoring the responses there is no confusion between prior-list intrusions and current-list intrusions. Second, when the items are presented, it is evident to the participants which items are to be recalled (i.e., the word presented alone after the comparison pair) and which items are not to be recalled (i.e., the comparison pair words). Hence, if participants mistakenly recall words from the comparison pairs (i.e., make current-list intrusions), they do so because they fail to exclude the comparison pair words from the memory set, not because they were unsure whether or not these words were appropriate for recall at presentation. SICSPAN also has a structural advantage to number updating, which is important here. It closely resembles the “operation span” (OSPN) task commonly used to measure WMC (Engle, 2002). The structural similarities between the two tasks will require the participants to recruit common processes when performing them and hence it may be argued that SICSPAN is a more valid measure of WMC than number updating. The important difference between SICSPAN and other often used complex span tasks—such as OSPN, “reading span”, and “counting span”—is that SICSPAN makes it possible to measure intrusions from items that are part of the task but never meant for recall.

**EXPERIMENT 2**

The key aim of Experiment 2 was to test if the relationship between WMC and semantic auditory distraction depends on the efficiency with which people can exclude irrelevant items from a memory set as measured by current-list intrusions in the SICSPAN task. One methodological concern with analysing the relationship between different responses in the same task is that they must necessarily be negatively correlated (a high number of correct answers on SICSPAN is accompanied with a low number of intrusion errors in the same task). To overcome this problem we included

<table>
<thead>
<tr>
<th>Part of task</th>
<th>Items presented</th>
<th>Required cognitive mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing</td>
<td>“Is COW larger than CAT?”</td>
<td>Exclude “cow” and “cat”</td>
</tr>
<tr>
<td>Memory</td>
<td>“CROCODILE”</td>
<td>Include “crocodile”</td>
</tr>
<tr>
<td>Processing</td>
<td>“Is TURTLE smaller than MOUSE?”</td>
<td>Exclude “turtle” and “mouse”</td>
</tr>
<tr>
<td>Memory</td>
<td>“LION”</td>
<td>Include “lion”</td>
</tr>
<tr>
<td>Recall</td>
<td>Correct</td>
<td>Outcome</td>
</tr>
<tr>
<td></td>
<td>“Crocodile”</td>
<td>Correct “Crocodile”</td>
</tr>
<tr>
<td></td>
<td>“Lion”</td>
<td>Correct “Lion”</td>
</tr>
<tr>
<td></td>
<td>Incorrect</td>
<td>Incorrect “Crocodile”</td>
</tr>
<tr>
<td></td>
<td>“Mouse”</td>
<td>Incorrect “Lion”</td>
</tr>
</tbody>
</table>

Figure 2. The size-comparison span task. The participants alternate between comparing the size of objects and remembering words. When pairs of size-comparison words are presented to the participants, the task is to respond “yes” or “no” to the question. Thereafter, a to-be-remembered word (e.g., CROCODILE) is presented that the participants should “include” in the memory set. When the to-be-remembered word disappears, a new comparison is made. During list presentation the participants should process the words in the size-comparison part of the task but “exclude” those words from the memory set. If the participants recall a word that belonged to a size-comparison pair (e.g., MOUSE), this is scored as a “current-list intrusion”.

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an OSPAN task and tested whether the relationship between OSPAN and semantic auditory distraction disappears when current-list intrusions in SICSPAN are statistically controlled for. Experiment 2 also explored if prior-list intrusions in OSPAN contribute to the effects of speech on prose memory. Prior-list intrusions in OSPAN measure recollection of items that once were relevant for recall. Note that current-list intrusions in SICSPAN, in contrast, measure recollection of items that were never relevant for recall. Unsworth and Engle (2006a) have shown that low-WMC individuals make more prior-list intrusion errors than do high-WMC individuals. The authors argued that prior-list intrusions reflect poor search of items in secondary memory and differences in the efficiency of this search mechanism are the reason why WMC task performance is related to higher-order cognition. The role of this search mechanism is intuitively evident in higher-order tasks that require the use of prior knowledge. Based on this account, it is not surprising to note that people who tend to make prior-list intrusions, exhibiting poor search of knowledge in secondary memory, also have poor reading comprehension (e.g., Lustig et al., 2001). However, the role of a similar mechanism in auditory distraction is not equally obvious. Since we argue that a mechanism responsible for the gating of exogenous information is responsible for people’s susceptibility to semantic auditory distraction, rather than a mechanism responsible for the search of items in secondary memory, it would be informative to investigate whether prior-list intrusions are related to semantic auditory distraction contrary to our expectations.

**Method**

**Participants**

A total of 42 people (20 women) with a mean age of 33.50 (SD = 6.62) took part in Experiment 2. None of them took part in Experiment 1. All participants were native Swedish speakers, and reported normal or corrected-to-normal vision, normal hearing, and normal reading skills. The participants received a cinema ticket for participation.

**Tasks**

**Operation span.** A computerised version of the operation span task developed by Turner and Engle (1989) was adopted. In this task, mathematical operations such as “IS (6 + 4) × 2 = 20?” were presented on the computer screen. The participants were asked to answer “yes” or “no” to the question by pressing a button on the keyboard, applying a self-paced mode. They were encouraged to respond as accurately and quickly as possible. After they had pressed the button, the screen went blank and then a one-syllable noun (e.g., CAT) was presented on the screen for 1 second, which the participants were told to remember for later recall. When the to-be-remembered word disappeared, a new mathematical operation was presented or the list ended, depending on the length of the list. The list length (i.e., the number of words to be remembered) varied between two and six. The words within a list were semantically unrelated, and each word was presented only once during the task. When the last word in each list had been presented, the participants were instructed to recall as many of the words as they could remember in the order of presentation by typing on the computer keyboard. Recall was self-paced. The total number of lists was 10 (i.e., 2 of each list length) and the lists were presented in the same random order for each participant. The participants’ OSPAN score was the sum of all words recalled in each list completely and accurately recalled (i.e., an absolute-scoring procedure was adopted, as traditionally used, e.g., Unsworth & Engle, 2007a). For instance, if the participants recalled all four words in the correct serial position on a four-operations list, they would receive 4 points for that list, but if four out of five words were recalled on a five-operations list, they would receive 0 points for that list. When the participants recalled a word presented on previous trials, this was scored as a prior-list intrusion.

**Size-comparison span.** In the size-comparison span task, pairs of size-comparison words were presented on the screen (e.g., “Is JACKET smaller than SHOE?”). The participants were asked to answer “yes” or “no” to the question by pressing a button on the keyboard, applying a self-paced mode. They were encouraged to respond as accurately and quickly as possible. After they had pressed the button, the screen went blank and then a to-be-remembered word (e.g., SOCK) was presented on the screen for 1 second. When the to-be-remembered word disappeared, a new pair of size-comparison words was presented or the list ended, depending on the length of the list. The list length varied between two and six to-be-remembered words. All words (i.e., the size-comparison words and the to-be-remembered
words) within a list were taken from the same semantic category (e.g., clothes). No semantic category was repeated between lists and each word was presented only once during the task. When the last word in each list had been presented, the participants were instructed to recall as many of the to-be-remembered words as possible in the order of presentation by typing on the computer keyboard. Recall was self-paced. The total number of lists was 10 (i.e., two of each list length) and the lists were presented in the same random order for each participant. The participants’ responses were scored in two ways. Their SICSPAN score was the sum of all words recalled in each list completely and accurately recalled. A word presented in a size-comparison pair but still recalled at the end of the trial was scored as a current-list intrusion.

**Prose memory.** This task was the same as in Experiment 1.

**Design and procedure**

A within-participants design was used. The procedure was the same as in Experiment 1 with the following exceptions. The experimental setting involved two phases. In the first phase the participants conducted the operation span task and the size-comparison span task. In the second phase the participants conducted the prose memory task twice: once during quiet and once while exposed to the meaningful irrelevant speech presented over headphones. The speech was the same as in Experiment 1. The order between the tasks within phases was counterbalanced between participants. The experiment lasted for approximately 60 minutes.

**Results**

**Prose memory**

A total of 17 paragraphs (2%) were reported as not completely read. Hence the prose memory task was scored as in Experiment 1. As can be seen in Table 1, irrelevant speech impaired the participants’ performance on the task. A 2 (background condition: silence vs speech) × 2 (condition order: silence first vs speech first) analysis of variance revealed a significant difference between the background conditions, F(1, 40) = 12.25, MSE = 0.01, p < .01, η² = .23. The analysis neither found a main effect of condition order nor an interaction between condition order and background condition, both F < 1.

**Working memory capacity tasks**

The mean score on OSPAN was 20.29 (SD = 10.35; range 3–40), the mean score on the mathematical operation part was 37.19 (SD = 2.83; range 27–40), and the mean number of prior-list intrusions in OSPAN was 1.31 (SD = 1.94; range 0–10). The correlation between OSPAN score and operation-score was positive and significant, r(40) = .33, p < .05. A negative correlation would have indicated a trade-off between processing the operations and remembering the words. The positive correlation indicates no such trade-off. A common way to control for this trade-off is to exclude all participants whose performance in the operation part is below 85%. In our sample four participants scored below 85%, but their OSPAN score was also low compared with the sample mean and their latencies on the operation part did not indicate that they skipped the operation part of the task. Therefore we decided to include them in the analyses.

The mean score on SICSPAN was 16.64 (SD = 8.81; range 2–40) and the mean score on the comparison part was 36.38 (SD = 3.93; range 23–40). The correlation between SICSPAN score and comparison score was positive and significant, r(40) = .40, p < .01. Hence there was no trade-off between processing the comparisons and remembering the words. The mean number of current-list intrusions from the size-comparison pairs into the recall of memory items was 2.56 (SD = 2.86; range 0–14). Notably, there was a total absence of prior-list intrusions in SICSPAN. This result was expected since each trial involved words from the same semantic category, whereas no category was repeated between trials, indicating that the item confusion observed with current-list intrusions in SICSPAN occurs within a semantic category, not across categories.

The participants’ OSPAN and SICSPAN scores were highly correlated, r(40) = .63, p < .01, a finding which suggests that the two tasks share common processes. The current-list intrusions in SICSPAN correlated negatively and significantly with SICSPAN score, r(40) = −.62, p < .01 and, importantly, with OSPAN score, r(40) = −.55, p < .01, a finding which suggests that participants who are susceptible to current-list intrusions in SICSPAN are the ones who score low on OSPAN. Therefore, the mechanism measured by
current-list intrusions in SICSPAN may underlie a relationship between OSPAN and semantic auditory distraction.

The relationship between working memory capacity and semantic auditory distraction

To recapitulate, the sub-process view of WMC suggests that individual sub-processes are related to semantic auditory distraction, not WMC as a unitary construct. The hypothesis of concern here is that current-list intrusions in SICSPAN, assumed to measure an inclusion/exclusion mechanism, are responsible for the relationship between WMC and semantic auditory distraction, whereas another sub-process measured by prior-list intrusions in OSPAN is not. To test these assumptions, hierarchical regression analyses were performed following the same rationale as outlined in Experiment 1. First, the relationship between semantic auditory distraction and individual predictors (SICSPAN score, OSPAN score, current-list intrusion errors in SICSPAN, and prior-list intrusion errors in OSPAN) were analysed in separate regression models. Second, a separate set of analyses tested whether the relationship between SICSPAN score and semantic auditory distraction would disappear when the current-list intrusions were entered into the regression model. Similarly, a separate set of analyses tested whether the relationship between OSPAN score and semantic auditory distraction would disappear when current-list intrusions were entered into the regression model. Finally, the contribution from current-list intrusions and prior-list intrusions where compared in a separate set of regression analyses (Table 3).

First, the contribution from SICSPAN scores and current-list intrusions was investigated. We calculated a hierarchical regression analysis with prose memory in the speech condition as dependent variable, prose memory in the silent condition and condition order as independent variables in the first step, SICSPAN scores as independent variable in the second step, and current-list intrusions in SICSPAN as independent variable in the third step. The regression model was significant in all steps, $R^2 = .54$, $F(2, 39) = 22.81$, $MSE = .01$, $p < .01$ (in the first step). Prose memory in the silent condition explained a significant part of the variance, $\beta = .73$, $t = 6.69$, $p < .01$ (in the first step), whereas condition order did not, $\beta = .11$, $t = 1.01$, $p = .32$ (in the first step). Adding SICSPAN scores in the second step explained a significant part of the residual variance not explained by prose memory in the silent condition, $\Delta R^2 = .10$, $\beta = .34$, $t = 3.34$, $p < .01$. However, when current-list intrusions were entered in the third step of the regression model, SICSPAN scores no longer explained a significant part of the variance, $\beta = .14$, $t = 1.20$, $p = .24$, but so did the current-list intrusions, $\Delta R^2 = .06$, $\beta = - .31$, $t = - 2.65$, $p < .05$. Another hierarchical regression analysis was calculated with SICSPAN scores and current-list intrusions added to the model in reversed order. When current-list intrusions were entered in the second step of the analysis, it explained a significant part of the variance, $\Delta R^2 = .16$, $\beta = -.39$, $t = - 4.28$, $p < .01$, but adding SICSPAN scores in the third step of the analysis did not explain another significant part of the variance, $\Delta R^2 = .01$, $\beta = .14$, $t = 1.20$, $p = .24$, although the current-list intrusions still did, $\beta = - .31$, $t = -2.65$, $p < .05$.

Second, the contribution from the OSPAN scores to semantic auditory distraction was investigated. This was made with the same type of analysis as above but with OSPAN scores instead of SICSPAN scores. Adding OSPAN scores to the analysis in step two explained a significant part of the residual variance not explained by prose memory in the silent condition, $\Delta R^2 = .10$, $\beta = .33$, $t = 3.35$, $p < .01$. However, when the current-list intrusions in SICSPAN were entered in the third step of the regression model, they explained a significant part of the residual variance, $\Delta R^2 = .07$, $\beta = -.30$, $t = - 2.80$, $p < .01$, while OSPAN score no longer explained a significant part of the variance, $\beta = .16$, $t = 1.49$, $p = .15$. Another hierarchical regression analysis was calculated with OSPAN scores and current-list intrusions in SICSPAN entered in the reversed order. Adding current-list intrusions to the analysis in the second step explained a significant part of the variance, $\Delta R^2 = .16$, $\beta = -.39$, $t = - 4.28$, $p < .01$, but adding OSPAN scores in the third step of the analysis explained no significant part of the variance, $\Delta R^2 = .02$, $\beta = .16$, $t = 1.49$, $p = .15$, whereas current-list intrusions still did, $\beta = -.30$, $t = -2.80$, $p < .01$. Hence, current-list intrusions in SICSPAN seem to measure some mechanism that underlies the relationship between WMC and semantic auditory distraction.

Third, the contribution from prior-list intrusions in OSPAN and current-list intrusions in SICSPAN was compared. A hierarchical regression analysis was calculated as above, but with prior-list intrusions in OSPAN as dependent variable in the second step, and current-list intrusions in SICSPAN as independent variable in the third
step. Adding prior-list intrusions in OSPAN to the regression model in the second step did not add to the explanatory power of the model, $\Delta R^2 = .04$, $b = -.16$, $t = -1.49$, $p = .15$, but adding current-list intrusions in SICSPAN in the third step did explain another significant part of the variance, $\Delta R^2 = .13$, $b = -.40$, $t = -3.85$, $p < .01$, whereas the prior-list intrusions still did not, $b = .02$, $t = 0.21$, $p = .84$. Another hierarchical regression analysis was calculated with the prior-list intrusions in OSPAN and the current-list intrusions in SICSPAN entered in reversed order. Adding current-list intrusions to the model in the second step explained a significant part of the variance, $\Delta R^2 = .16$, $b = -.39$, $t = -4.28$, $p < .01$, but adding prior-list intrusions to the model in the third step explained no additional variance, $\Delta R^2 < .01$, $b = .02$, $t = 0.21$, $p = .84$, whereas the current-list intrusions still did, $b = -.40$, $t = -3.85$, $p < .01$. Hence the mechanism measured by current-list intrusions in SICSPAN seems to be functionally distinct from the mechanism responsible for prior-list intrusions in OSPAN.

**Discussion**

The results from Experiment 2 are straightforward. Individual differences in the score on two complex span tasks (OSPA$\check{n}$ and SICSPAN) predict individual differences in susceptibility to the effects of speech on prose memory. However, these relationships disappear when intrusion errors from the size-comparison words in SICSPAN (i.e., current-list intrusions) are controlled for. Experiment 2 also found that prior-list intrusions do not predict effects of speech on prose memory. Current-list intrusions, in contrast, explain the effects of speech on prose memory even when prior-list intrusions are statistically controlled. It seems as if the mechanisms tapped by those two types of errors are functionally distinct.

The implication of these results is that there is no need for the concept “working memory capacity” in explaining the observed relationships. Rather, the relationship between the two complex span tasks and semantic auditory distraction is one between an inclusion/exclusion mechanism and semantic auditory distraction.

**GENERAL DISCUSSION**

The results from two experiments demonstrate that individual differences in people’s performance on three different working memory capacity (WMC) tasks (number updating, OSPAN, and SICSPAN) predict individual differences in susceptibility to the effects of speech on prose memory. The results also indicate that a specific
type of item confusion error, committed when participants recall items that are part of the task but never intended for recall, is responsible for the relationship between WMC and semantic auditory distraction. Furthermore, the results suggest that another type of item confusion error, committed when participants recall items that once were appropriate for recall but subsequently became inappropriate, is not related to semantic auditory distraction. These findings agree with previous investigations (Beamam, 2004; Sörgqvist et al., 2010).

Implications for theories of semantic auditory distraction

Beamam (2004) suggested that a source-monitoring failure might cause semantic auditory distraction (see also Bell et al., 2008; Marsh et al., 2008, 2009). Source-monitoring failure also holds as an explanation of the relationship found here between current-list intrusions in SICSPAN and the effects of speech on prose memory. Current-list intrusions are observed when participants mistakenly recall words from the processing part of the SICSPAN task that are never intended for recall (see Figure 2). The participants may well commit this type of error because they fail to appropriately monitor the source of the words presented during the processing part. However, the relationship between immediate intrusions in the number-updating task and semantic auditory distraction found here and elsewhere (Sörgqvist et al., 2010) can hardly be explained in terms of source monitoring. Immediate intrusions in number updating are observed when the participants recall numbers that are part of the task but do not reach the criterion for recall (see Figure 1). This latter finding is probably better explained in terms of failed “relevance monitoring” (i.e., a failure to map specific responses to stimuli that reach a certain relevance criterion and only to those stimuli). In the number-updating task the participants’ goal-directed behaviour is to substitute items in working memory when appropriate. Hence they must actively avoid responding with this behaviour when presented with a number too large to reach the recall criterion. Otherwise they will enclose the irrelevant number in the memory set, which will lead to errors.

Similarly, people may be susceptible to semantic auditory distraction because they involuntarily respond with the goal-directed processing to wrong stimuli. For instance, when the participants are reading prose their goal-directed behaviour is to process the meaning of the text materials. When reading in the presence of background speech, they must monitor the relevance of the text and the speech materials and inhibit the act of mapping the goal-directed processing of meaning onto the speech materials. If they do not do this, distraction takes place. The proposition that relevance monitoring causes semantic auditory distraction rests on the assumption that immediate and current-list intrusion errors are made when participants mistakenly respond with the goal-directed process to wrong, exogenous, stimuli (see Sörgqvist & Setrevik, in press, for an fMRI study that supports this possibility). However, it should be noted that the nature of the mechanism responsible for intrusion errors in WMC tasks is a matter of debate (see Dempster & Corkill, 1999, and Oberauer & Lange, 2008, for discussions of different mechanisms).

Functionally independent mechanisms covered by the WMC construct

Why does WMC predict individual differences in susceptibility to semantic auditory distraction? We believe that WMC is related to semantic auditory distraction because WMC tasks measure an inclusion/exclusion mechanism that inhibits or blocks the goal-directed process when exogenous materials do not reach a certain relevance criterion. Two results reported here are particularly relevant to this argument: first, immediate intrusions in the number-updating task and current-list intrusions in SICSPAN are related to semantic auditory distraction; and second, the relationship between OSPAN and semantic auditory distraction disappears when current-list intrusions in SICSPAN are taken into account, whereas the current-list intrusions remain significantly related to distraction. Another similar finding has been reported by Conway, Cowan, and Bunting (2001). Using a classic dichotic listening procedure, these authors found that high-WMC individuals are less likely to notice their own name spoken in a speech stream denoted as irrelevant while repeating aloud what is said in another, relevant stream of speech. This result is easy to assimilate with the idea that WMC covers a mechanism responsible for blocking the goal-directed processes (in this case to listen to a specific speech stream) from being
of the sub-process view of WMC, the findings can
cover functionally distinct mechanisms. In terms
responsible for those individual differences.
the gating of incoming materials would be re-
inclusion/exclusion mechanism responsible for
an intuitive level, it is more obvious why an
ability to disruption from exogenous materials. On
search of items in secondary memory can be
appreciate how a mechanism responsible for the
memory; and second, it is difficult to intuitively
updating predict the effects of speech on prose
stream).

Why does WMC predict individual differences
in reading comprehension? Delayed intrusions in
the number-updating task are observed when
participants recall items that once were relevant,
but subsequently became no longer relevant for
recall within the same trial. It has been shown
that delayed intrusions are responsible for the
relationship between WMC and reading compre-
hension (Carretti et al., 2005). Furthermore, this
type of error closely resembles the empirical
signature of “proactive interference” (i.e., prior-
list intrusions). The significance of proactive
interference to individual differences in WMC
has been shown by Lustig et al. (2001). The
authors manipulated the build-up of proactive
interference in a reading span task and showed
that proactive interference is responsible for the
relationship between WMC and reading compre-
hension. Given the similarities between delayed
and prior-list intrusions, it seems safe to assume
that they measure the same underlying mechan-
ism. Based on this, we suggest that individual
differences in the ability to delete or suppress
irrelevant items in secondary memory (measured
by delayed and prior-list intrusions) drive the
relationship between WMC and reading compre-
hension. This is conceptually similar to Unsworth
and Engle’s view according to which WMC is
related to higher-order cognition because WMC
tasks measure the ability to limit the search for
items in secondary memory (Unsworth, 2007;
Unsworth & Engle, 2006a, 2006b, 2007b). The
important point to make here, however, is that
the deletion/suppression mechanism is qualita-
tively different from the inclusion/exclusion me-
chanism, and is not related to semantic auditory
distraction because, first, neither prior-list intru-
sions in OSPAN nor delayed intrusions in number
updating predict the effects of speech on prose
memory; and second, it is difficult to intuitively
appreciate how a mechanism responsible for the
search of items in secondary memory can be
responsible for individual differences in suscept-
ibility to disruption from exogenous materials. On
an intuitive level, it is more obvious why an
inclusion/exclusion mechanism responsible for the
gating of incoming materials would be re-
sponsible for those individual differences.

Taken together, the WMC construct seems to
cover functionally distinct mechanisms. In terms
of the sub-process view of WMC, the findings can
be summarised in the following formula:
“WMC = an inclusion/exclusion mechanism + a
deletion/suppression mechanism + . . . + mechanismn”.
The inclusion/exclusion mechanism is re-
lated to semantic auditory distraction but not
to reading comprehension, and the deletion/
suppression mechanism is related to reading
comprehension but not to semantic auditory
distraction. The reason why WMC is related to
both reading comprehension and semantic audi-
dory distraction is simply because it is the sum of
the contributions from those functionally inde-
pendent sub-processes. The aim of future investi-
gations within this framework is to identify
independent sub-processes and specify how they
are related to other phenomena instead of think-
ing of WMC as a single measure. For example,
traditional complex span tasks require order
processing since the participants are requested
to recall the items in order of presentation
(Conway et al., 2005). The contribution from
order processing to complex span task perfor-
mance may therefore be observed by transposi-
tion errors (i.e., the correct items are recalled but in
wrong serial position). In terms of the sub-process
view, transposition errors measure a sub-process
(e.g., order processing) different from the inclusion/
exclusion and the deletion/suppression mechani-
sms, and transposition errors may therefore have
unique correlative properties. For instance, com-
plex span scores correlate with simple span scores
(Engle et al., 1999; Unsworth & Engle, 2007a).

Conclusion

In the present paper we have outlined a new
perspective of WMC, which we have called
the sub-process view, with the ambition to be specific
regarding the particular processes that underlie
the correlations between WMC and higher-order
cognition. The first impression is that WMC is
related both to semantic auditory distraction and
to reading comprehension. However, in support
for the sub-process view, the results presented
here and elsewhere (Carretti et al., 2005; Lustig
et al., 2001; Sörqvist et al., 2010) suggest that
WMC per se is related neither to semantic
auditory distraction nor to reading comprehen-
sion. By looking beneath the surface, it seems like
a specific and measurable part of the WMC construct is related to semantic auditory distraction, whereas another part is related to reading comprehension, and when controlling for specific sub-processes statistically, the correlations between overall WMC task scores and other phenomena disappear.

REFERENCES


Effects of aircraft noise and speech on prose memory: What role for working memory capacity?

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Abstract
Previous research indicates that aircraft noise and meaningful background speech are particularly detrimental to school adolescents' ability to remember what they read, but until now the effects from aircraft noise and speech have never been compared directly in an experiment. Furthermore, individual differences in susceptibility to these effects are not well understood. The present investigation addressed these two issues. Adolescents attending upper secondary school were recruited as participants and the data collection was made in their ordinary classrooms. The results from two experiments revealed that speech is more detrimental to prose memory than is aircraft noise, and individual differences in working memory capacity contribute more to individual differences in susceptibility to the effects of aircraft noise on prose memory than to the effects of speech. Some applied implications of those findings to noise abatement interventions are suggested.

1. Introduction
Learning by reading is the linchpin of regular school education. People's ability to learn from texts determines their academic success and will have a strong influence on their lives. Hence, it is most unfortunate but still well established that noisy school environments provide serious barriers for adolescents' ability to remember what they read (for reviews, see Beaman, 2005a; Shield & Dockrell, 2003). Two noteworthy observations can be made from this line of research. The first observation concerns differences in effect magnitude between noises and the second observation concerns individual differences in susceptibility to these effects, both of which are addressed in the present investigation.

Research that aims to compare different environmental noises is mainly applied in nature. Specifically, the results from such investigations have implications for the formulation of acoustic standards and they inform decision makers how to best allocate limited noise abatement resources. In a series of classroom experiments, Hygge (2003) demonstrated that the effect from aircraft noise on prose memory exceed the effect from road traffic noise, train noise, and speech from a foreign language. Hygge did not include a condition with speech meaningful to the participants. However, meaningful irrelevant speech has also repeatedly been shown to have larger effects on prose memory in comparison with several non-speech sounds (Boman, 2004; Hygge, Boman, & Enmarker, 2003; Oswald, Tremblay, & Jones, 2000). Because of this, aircraft noise and irrelevant speech stands out as two particularly detrimental types of noises. However, thus far their effects have never been compared experimentally.

Based on some major theories of auditory distraction, one would expect prose memory to be more disrupted by speech than by aircraft noise. One of those theories is the interference-by-process account by Jones and colleagues (e.g., Macken, Tremblay, Alford, & Jones, 1999; Marsh, Hughes, & Jones, 2008). According to this theory, disruption is a function of the similarity of the processes required by the primary task (in this case reading) and the processes required by listening to the sound. Speech should therefore be particularly detrimental to prose memory because the automatic processing of the semantic content in speech sounds will compete with the deliberate processing of the semantic content in the prose material. Since listening to non-speech sounds, such as aircraft noise, does not require processing of meaning, prose memory should not be as disrupted by aircraft noise. A second theory intended to explain effects of speech on cognitive processes is the phonological loop account proposed by Baddeley and colleagues (e.g., Salamé & Baddeley, 1982). This theory also suggests that speech should be more detrimental to prose memory than aircraft noise, although the explanation is different from the one made by the interference-by-process account. According to Baddeley's theory, phonological information from the speech sound is automatically encoded into a phonological store where it meets phonological information encoded from the text while reading.

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disruption caused by the sound is a function of the phonological similarity between the sound and the materials within the phonological store. Since aircraft noise does not contain phonological information, aircraft noise should not produce disruption according to this theory. A third theory proposed to explain effects of noise on cognitive performance is the one by Cowan (1995). This theory assumes that noise depletes attentional resources which otherwise could have been used to entertain the primary task. Unexpected or surprising sound events are assumed to draw attention away from the task and disrupt performance. A speech sound should hence be more detrimental to prose memory when it contains unexpected sound events, but in principle it should be possible for an aircraft noise to be more disruptive than speech.

In addition to comparing the effects of aircraft noise and speech, the present investigation aims to study individual differences in susceptibility to those effects. Differences in susceptibility to auditory distraction have received much attention during the last decade (e.g., Beaman, 2005b; Bell & Buchner, 2007; Ellermann & Zimmer, 1997; Elliott, Barrileaux, & Cowan, 2006; Elliott & Cowan, 2005; Macken, Phelps, & Jones, 2009), but besides speech, only a few of those studies have concerned noise typical in the “everyday” environment (e.g., transportation noise such as aircraft noise). The few exceptions include a study by Boman, Enmarker, and Hygge (2005) which concerned the effects of road traffic noise amongst people of different ages, and a study by Dockrell and Shield (2006) which concerned the effects of children’s babble on pupils with special educational needs.

It has since long been argued that the processing of acoustic change is a fundamental basis of auditory distraction (e.g., Cowan, 1995; Jones & Macken, 1993) and recently Macken et al. (2009) showed that people who are good at processing acoustic change are more distracted by sound than others, at least when distraction is measured by a reduction in serial recall of sequences of digits. However, during the last five years of so, several investigators have stressed the importance of working memory capacity (WMC) in explaining differences in susceptibility to auditory distraction. WMC is commonly measured by the operation span (OSPAN) task introduced by Turner and Engle (1989). This task requires participants to remember a sequence of words and simultaneously calculate mathematical operations. People’s performance on OSPAN is related to several cognitive abilities and constructs including general intelligence (Unsworth & Engle, 2005). This suggests that an OSPAN score reflects a very general cognitive capacity. In particular, according to the WMC theory by Engle and colleagues (e.g., Kane, Blecley, Conway, & Engle, 2001) participants’ performance on OSPAN reflects their ability to focus attention of the task at hand in the presence of irrelevant materials. Based on this theory one would expect WMC to predict the ability to solve cognitive tasks in the presence of auditory distraction. In line with this assumption, it has been shown that individuals with low WMC are more distracted by background speech while reading (Sörqvist, Halin, & Hygge, 2009; Sörqvist, Ijungberg, & Ijung, submitted for publication), more susceptible to intrusions from speech words into the recall of memory items (Beaman, 2004), more susceptible to distraction from hearing one’s own name spoken in the background (Conway, Cowan, & Bunting, 2001), and more distracted by changing-state tones while performing a serial recall task (Elliott et al., 2006) than are individuals with high WMC. In light of these observations, it could be argued that noise abatement resources should first of all be allocated to people with poor WMC. However, the relationship between WMC and susceptibility to distraction from transportation noise and other naturally existing noise sources have never been investigated. Without such investigations it is uncertain if WMC also plays a role in more ecologically valid situations. The objectives of the present investigation were twofold. First, it aimed to compare the effects of aircraft noise and speech on school adolescents’ prose memory. Second, it aimed to explore the relationship between WMC and susceptibility to those effects.

1. Experiment 1–2

An ecologically valid but still well controlled approach was desired in the present investigation. To this end, two experiments were conducted in ordinary upper secondary school classrooms and the adolescents attending these schools were tested together with their classmates in groups of about 20 individuals. The relationship between WMC and susceptibility to the effects of aircraft noise and speech on prose memory was examined in Experiments 1a and 1b respectively. Experiment 2 compared the effects of speech and aircraft noise directly. The data collection for Experiments 1a and 1b was made at the same time with participants from the same classes, but reported separately on readability. This was considered a methodologically better approach than to recruit different classes for different experiments because between-study comparisons would otherwise be strongly influenced by between-participants variability.

2. Experiment 1a

The purpose of Experiment 1a was to test the hypothesis that there is a relationship between adolescents’ WMC and their susceptibility to effects of aircraft noise on prose memory.

2.1. Method

2.1.1. Participants

Twenty-five adolescents were recruited from three upper secondary school classes in Sweden. Two reported having problems with reading (e.g., dyslexia) and were removed prior to the analyses. The remaining 23 individuals (14 females and 9 males) were approximately 17 years old and reported normal hearing ability, normal reading skills and Swedish as their native tongue. “Normal hearing ability” was established by asking the participants whether or not they have had attenuated hearing. This procedure appeared to be sufficient for the present purposes because all pupils in Sweden take part in an audiogram screening from which they will know whether or not they have hearing loss. All participants received a cinema ticket as compensation.

2.1.2. Aircraft noise

Sounds from different airborne aircrafts were recorded outside using a stereophonic microphone. The sounds were put together with computer software so as to create 10 sound sequences of aircrafts passing by the listener (i.e., it sounded as if aircrafts was flying by, one by one, without overlap). Each sequence was 1 min long and contained 3–4 passing aircrafts (see Fig. 1). The sounds were filtered with computer software as if it had passed through a brick wall. The brick wall was simulated using an octave band equalizer (1024 bin FIR filters), adjusting the decibel levels of specific octave bands (<31 Hz: +6 dB; 63 Hz: +6 dB; 125 Hz: 0 dB; 250 Hz: –6 dB; 500 Hz: –6 dB; 1 kHz: –12 dB; 2 kHz: –17 dB; 7 kHz: –22 dB; 8 kHz: –27 dB; >16 kHz: –36 dB). The purpose of this manipulation was to make the sound perceived as indoors.

2.1.3. Tasks

2.1.3.1. Operation span.

A computerized version of the OSPAN task was used to assess the participants’ WMC. In this task, mathematical operations such as “15 (4 ∙ 2) ÷ 3 = 187” were presented on a computer screen. The participants’ task was to respond “yes” or
"no" with a button press depending on the validity of the equation. After pressing the button, a one-syllable noun (e.g., CAT) was presented on the screen for 1 s, and thereafter a new operation was presented or the list ended depending on the length of the list. The list length varied between 2 and 6 operation-word pairs. When the last word had been presented, the participants were instructed to recall as many of the words as they could remember in order of presentation by typing on the computer keyboard. The total number of lists was 16 (i.e., three of each list length and one practice trial) and the lists were presented in the same random order for each participant. The responses were scored by a strict serial recall criterion giving one point for each word recalled in the correct serial position.

2.1.3.2. Prose memory. Two prose memory tasks were developed each consisting of 10 short paragraphs. The paragraphs in one task told the story of a fictitious culture called “the Lobiks” and the paragraphs in the other task told the story of another fictitious culture called “the Timads”. The participants read an instruction for the task before they began which told them to ignore any sound they might hear and read the paragraphs thoroughly in order to answer questions later on. The task consisted of two phases: one reading phase and one recall phase. In the first phase, the paragraphs were presented sequentially on the computer screen (each displayed for 60 s). When a paragraph disappeared the participants were asked if they had been able to read the whole text. In the aircraft noise condition, each paragraph within the task was accompanied by one of the sound sequences.

Fig. 1. The figure shows the aircraft noise’s level (A-weighted decibel) across time (60 s). Each line represents 1 of the 10 sound files including 3–4 different airborne aircrafts passing by the listener. Each of the 10 paragraphs in the prose memory task was accompanied by one of the sound sequences.

The figure shows the aircraft noise’s level (A-weighted decibel) across time (60 s). Each line represents 1 of the 10 sound files including 3–4 different airborne aircrafts passing by the listener. Each of the 10 paragraphs in the prose memory task was accompanied by one of the sound sequences.

2.1.4. Procedure

Laptop computers with headphones attached were rigged in the classrooms. The participants then entered the classrooms together and sat down at a computer chosen without influence from the experimenter. The participants began with performing the OSPAN task and thereafter the two prose memory tasks. The order of the prose memory tasks and the order of the background conditions (aircraft noise first vs. silence first) was balanced between participants (11 began in the aircraft noise condition and 12 began in the silent condition). As participants would work at different pace and complete the experimental tasks at different times, an additional task was added at the end of the experiment (i.e., after the last prose memory task) to engage the participants in a meaningful activity and not disturb the other participants in the room still working on the experimental tasks. The whole session lasted for about 60 min. When everyone was done, the participants were thanked and debriefed.

2.2. Results and discussion

The participants’ mean of words accurately recalled on the OSPAN task was 39.87 (SD = 10.81) and their mean of mathematical operations accurately responded to was 48.52 (SD = 79.3). The correlation between accuracy on the operations and words accurately recalled was not significant, r(21) = .39, p = .07, but close to significant. Hence, the participants did not use a trade-off strategy between processing the operations and remembering the words. On the prose memory task, a total of 26 paragraphs (6%) were reported as not completely read. Somewhat surprisingly, the participants reported more paragraphs as not completely read in the silent condition (M = .78, SD = 1.41) than in the aircraft noise condition (M = .35, SD = .78), t(22) = 2.10, p < .05. The difference was small however (about half a paragraph). Since not all paragraphs were read throughout, the answers were scored as proportions of the questions answered for paragraphs completely read. As can be seen in Table 1, the difference in mean prose memory score in the silent condition and in the aircraft condition was in the expected direction but did not reach significance. A 2
model increased condition order explained no significant part of the variance, memory in the silent condition, 

\( p < .01 \) (in the second step), and OSPAN score was significantly associated with the residual variance not explained by prose memory in the silent condition, \( \beta = .32, \ t = 2.51, \ p < .05 \), whereas condition order explained no significant part of the variance, 

\( t = 1.52, \ p = .19 \) (in the second step). Adding OSPAN score to the model increased \( R^2 \) from .64 in step 1 to .73 in step 2. These results suggest that the effect of aircraft noise on prose memory is larger for individuals with low WMC (explaining about 9% of the variance).

It’s perhaps not surprising that no main effect of aircraft noise was revealed in Experiment 1a. Studies reporting main effects of acute (Hygge, 2003) and chronic (Hygge, Evans, & Bullinger, 2002; Stansfeld et al., 2005) exposure to aircraft noise on cognitive performance have considered individuals younger than the participants in this experiment. Furthermore, Elliott (2002) has shown that the ability to avoid distraction from non-speech sounds increases throughout childhood. Hence, on a general level, people seem to become less distracted by aircraft noise in reaching adulthood, but low WMC individuals are still particularly vulnerable.

### Table 1

| Experiment | Aircraft noise | Silence | 1.50 | .24 | .14 | 1.67 | .07 |
| Experiment 1b | Speech | Silence | .11  | .28 | .16 | 10.44* | .33 |
| Experiment 2 | Speech | Aircraft noise | .05 | .12 | 8.45* | .18 |

Note: All experiments are within-subject. The participants in Experiment 2 were older and attended a school program different from the other participants which may explain the large between-experiment differences in prose memory score. * \( p < .01 \).

3. **Experiment 1b**

The objective of Experiment 1b was to investigate the relationship between adolescents’ WMC and their susceptibility to the effects of speech on prose memory. This relationship has been found using approximately the same tasks as in the present investigation (Sörqvist et al., submitted for publication) and a range of other studies have demonstrated relationships between WMC and the effects of speech on cognitive performance (Beam et al., 2004; Conway et al., 2001; Sörqvist et al., 2009). Because of this, the relationship was expected here as well.

### 3.1. Method

#### 3.1.1. Participants

Twenty-nine adolescents from three upper secondary school classes were recruited for Experiment 1b. Six reported problems with reading, hearing loss, or not having Swedish as a native language. They were removed before the analyses. The remaining 23 individuals (17 females and 6 males) were about 17 years old and reported normal hearing ability, normal reading skills and Swedish as their native tongue. All participants received a cinema ticket as compensation.

#### 3.1.2. Materials and procedure

The speech was recorded in an echo-free room and consisted of a story about a fictitious culture called “the Ansarians” told by a male actor. The recording was divided into 10 segments. Silent pauses (e.g., breaks between sentences) were adjusted so as to maintain a fairly constant flow of words. The loudness of the speech was equalised with the aircraft noise used in Experiment 1a. The procedure of Experiment 1b was identical to the procedure in Experiment 1a, with the single exception that speech sounds were played instead of aircraft noise. The order of the background conditions could not be entirely balanced between participants (10 began in the silent condition and 13 began in the speech condition).

### 3.2. Results and discussion

The mean of words accurately recalled on the OSPAN task was 41.30 (SD = 10.81) and the mean of operations accurately responded to was 50.35 (SD = 6.42). As in Experiment 1a, there was no negative correlation between calculation accuracy and words accurately recalled, \( r(21) = .21, \ p = .33 \). On the prose memory tasks, a total of 23 paragraphs (5%) were not completely read. The number of paragraphs not completely in the speech condition \( (M = 48, \ SD = 1.12) \) did not differ from those in the silent condition \( (M = 26, \ SD = 6.95) \), \( F(21) = 1.31, \ p = .20 \). Since not all paragraphs were completely read, the prose memory tasks were scored the same way as in Experiment 1a. As can be seen in Table 1, there was a large and significant difference in the expected direction between prose memory score in the two conditions. A 2 (background condition: silence vs. aircraft noise) × 2 (condition order: silence first vs. aircraft noise first) analysis of variance revealed no main effect of background condition, \( F(1, 21) = 1.67, \ MSE = .01, \ p = .21, \ r^2 = .07 \), and no main effect of condition order, \( F < 1 \), and no interaction between the variables, \( F < 1.68, \ MSE = .20 \). Since not all paragraphs were completely read, the prose memory tasks were scored the same way as in Experiment 1a. As can be seen in Table 1, there was a large and significant difference in the expected direction between prose memory score in the two conditions. A 2 (background condition: silence vs. speech) × 2 (condition order: silence first vs. speech first) analysis of variance revealed a large main effect of speech on prose memory, \( F(1, 21) = 10.44, \ MSE = .01, \ p < .01, \ r^2 = .33 \), but no main effect of condition order, \( F(1, 21) = 1.50, \ MSE = .03, \ p = .24, \ r^2 = .07 \), nor an interaction between the variables, \( F < 1 \). A hierarchical regression analysis with prose memory in the speech condition as dependent variable, prose memory in the silent condition and condition order as independent variables in the first step, and participants’ score on OSPAN (i.e., words accurately recalled) as independent variable in the second step was calculated. This analysis could not support the hypothesis that high WMC individuals are less susceptible to speech distraction than are low WMC individuals since OSPAN score did not explain a significant part of the variance, \( \beta = .19, \ t = .75, \ p = .46 \).

Even though the relationship between OSPAN score and distraction in Experiment 1b was non-significant, it was in the expected direction and would possibly have reached significance given sufficient statistical power. Using approximately the same tasks, Sörqvist et al. (submitted for publication) detected the relationship with 42 participants. Yet, Experiment 1b still has merit. Taken together with the results from Experiment 1a, the results indicate (a) that speech has a larger effect on prose...
memory than aircraft noise and (b) that WMC is more important in characterizing people’s ability to filter out distraction from aircraft noise than from speech. In order to test these hypotheses directly, the effects of speech and aircraft noise were compared in Experiment 2.

4. Experiment 2

Since both aircraft noise and speech have already been compared with silence in Experiment 1a and 1b respectively, the silent condition was left out of Experiment 2 to minimize problems with unbalanced test difficulty and order effects. Based on previous investigations (Elliott, 2002; Elliott et al., 2006; Marsh et al., 2008; Martin, Wogalter, & Forlano, 1988; Oswald et al., 2000) and the results found in Experiment 1a and 1b, it was hypothesized that the participants’ prose memory score would be lower in the speech condition compared with the aircraft noise condition. Furthermore, the high WMC individuals’ prose memory score in the aircraft noise condition was expected to be higher than the low WMC individuals’ score after control for their prose memory score in the speech condition, based on the assumption that WMC is more important for filtering out distraction from aircraft noise than from speech.

4.1. Method

4.1.1. Participants

Fifty-three adolescents from two upper secondary school classes were recruited for Experiment 2. Thirteen reported problems with reading, hearing loss, or not having Swedish as a native language. They were removed before the analyses. The remaining 40 individuals (29 females and 11 males) were all approximately 18 years old and reported normal hearing ability, normal reading skills and Swedish as their native tongue. All participants received a cinema ticket for participation.

4.1.2. Materials and procedure

The materials and procedure of Experiment 2 were identical to those in Experiment 1a and 1b, with the exception that there was no silent condition. Instead, speech was played in one condition and aircraft noise was played in the other condition during the reading phase of the prose memory tasks. The order of the background conditions was entirely counterbalanced between participants (20 began with the speech condition and 20 began with the aircraft condition).

4.2. Results and discussion

The participants’ mean of words accurately recalled on the OSPAN task was 42.58 (SD = 9.90) and the mean of operations accurately responded to was 51.98 (SD = 4.46). The correlation between correct answers on the calculations and correct recall of variables, \( p = .03 \). A hierarchical regression analysis with prose memory in the aircraft noise condition as dependent variable, prose memory in the speech condition and condition order as independent variables in the first step, and OSPAN score as independent variable in the second step was calculated to test if the high WMC individuals’ prose memory score in the aircraft noise condition is higher than the low WMC individuals’ score after control for their prose memory score in the speech condition. The analysis revealed that prose memory in the speech condition explained a significant part of the variance in the aircraft noise condition, \( \beta = .58, t = 4.52, p < .01 \) (in the second step), and when OSPAN score was added in the second step of the analysis, it explained a significant part of the residual variance not explained by prose memory in the speech condition, \( \Delta R^2 = .06, \beta = .27, t = 2.14, p < .05 \). The variance explained by condition order did not reach significance, \( t < 1 \). These results confirm the hypothesis that WMC is more important for filtering out distraction from aircraft noise than from speech.

5. General discussion

The purpose of the present investigation was to compare the effects of aircraft noise and speech on prose memory, and to explore the role for WMC in those effects. Previous research has repeatedly demonstrated that meaningful speech and aircraft noise are particularly detrimental to prose memory compared with other types of sounds such as road traffic noise (Hygge et al., 2003) and train noise (Hygge, 2003), but the present investigation is the first to compare the two directly. The findings suggest that speech is more disruptive to prose memory than is aircraft noise, which is consistent with several theories of auditory distraction (e.g., Cowan, 1995; Marsh et al., 2008; Salamé & Baddeley, 1982).

It should be noted that the aircraft noise and speech used here differed on at least two aspects that may explain their different effects on prose memory. First, the physical properties such as frequency modulation were different. Second, speech involves semantic information while aircraft noise does not. It is well-known that changes in frequency across time contribute to auditory distraction, especially when the task is based on short-term serial memory (see Macken et al., 1999 for a review). The second sound property (i.e., semanticity) seems however to be more important when the task is to read and remember prose materials. For instance, prose memory is more disrupted by speech than by reversed speech (Bell, Buchner, & Mund, 2008; Oswald et al., 2000) even though reversed speech is similar to regular speech in terms of frequency modulation. The findings reported here do not tell how much the speech-like frequency modulation of speech sounds and the semantic component respectively contributes to the difference observed between the effects of speech and aircraft noise. Yet, the findings are in-line with other studies of auditory distraction of prose memory and may suggest that speech sounds is particularly disruptive to prose memory because of its semanticity, as stressed by the interference-by-process view of auditory distraction (Marsh et al., 2008).

Two mechanisms which underlie individual differences in auditory distraction have been identified (Sörqvist, submitted for publication(a)). One of them is the efficiency by which people process acoustic change in sounds (Mackens et al., 2009). This mechanism seems, however, only to determine susceptibility to auditory distraction when the task involves serial-order processing. The other mechanism is one related to WMC. Even though WMC seems important in a wider range of situations, such as in disruption of prose memory (Sörqvist et al., submitted for publication) and reading comprehension (Sörqvist et al., 2009) by background speech, false memories induced by speech (Beaman, 2004), and the cocktail party phenomenon (Conway et al., 2001), its role in
distraction produced by environmental sounds has never been shown before. The present study hence expands the role of WMC further by showing that it underlies people’s susceptibility to distraction produced by aircraft noise. Few investigations have compared susceptibility to different types of sounds and the present investigation makes a contribution in this regard by showing that WMC is more important to the filtering of aircraft noise than to the filtering of speech. These results are consistent with those reported by Elliott et al. (2006). The authors demonstrated a relationship between individuals’ OSPAN score and their susceptibility to serial recall by tone sequences, while they were not able to show a similar relationship with speech sequences. However, it is important to note that the absence of a significant relationship between OSPAN score and susceptibility to speech distraction reported in Experiment 1b was in the expected direction (i.e., negative). Also, there are several examples of relationships between OSPAN score and speech distraction in the literature (Beam, 2004; Conway et al., 2001) including a study from our own laboratory using approximately the same tasks as in the present investigation (Sörqvist et al., submitted for publication). Because of this, WMC is probably related to effects of speech on prose memory, yet not as strongly as to the effects of aircraft noise.

Why is the relationship between WMC and disruption from aircraft noise particularly strong? The interference-by-process account of auditory distraction (Marsh et al., 2008) as well as the phonological loop account (Salamé & Baddeley, 1982) suggests that automatic processes to a large extent underlie interference caused by background speech. Because of this, individual differences in attentional-control resources (i.e., WMC; see Kane et al., 2001) may be less relevant to the effects of speech on prose memory (since automatic processes by definition cannot be controlled). The availability to working memory resources has, however, been linked to attentional capture (e.g., Berti & Schröger, 2003; Conway et al., 2001; Sörqvist, submitted for publication). It may be in this regard that WMC is more strongly related to aircraft noise. That is, high WMC might attenuate the power of passing aircraft to capture the reader’s attention, whereas speech to some extent automatically interferes with the reading processes. This explanation is obviously speculative, but it is consistent with the idea that interference between similar cognitive processes is caused by a mechanism qualitatively different from attentional capture (Hughes, Vachon, & Jones, 2007; see also Sörqvist, submitted for publication). Even though some modest theoretical implications can be deduced from the present investigation as outlined above, the main contribution is applied in nature. The first applied implication is that interventions that aim to reduce the negative influence of irrelevant speech in classrooms should have particularly high priority, since speech stands out as the most devastating type of noise. The second applied implication is that noise abatement interventions would have the largest impact if individuals with low WMC would be given priority. The pool of low WMC individuals generally includes those with poor scholastic achievement (Gathercole, Pickering, Knight, & Stegmann, 2004) and low intelligence (Unsworth & Engle, 2005). In many school systems, pupils with poor scholastic achievement (and hence low WMC in general) are grouped together directly or indirectly by being selectively allocated to different school programmes. Because of this relative isolation of individuals with low WMC, it is possible to allocate noise abatement resources to them by, for example, providing them with special sound isolated classrooms. Obviously, this type of intervention would only attenuate the negative influence of noise generated from outside the classroom (e.g., aircraft noise), irrelevant speech and other types of noises generated from within the classroom can, for instance, be treated with other methods like masking music (Schlittmeier & Hellbrück, 2005) or increased reverberation (Beam & Holt, 2007). Yet, if decision makers have too choose between high- and low WMC individuals when allocating limited noise abatement resources, they should give priority to individuals with low WMC, because then they would reach individuals with a particular need for a non-disturking working environment more efficiently (cf. Sörqvist, submitted for publication(a)). This suggestion rests in part on the assumption that the sound used in the present investigation, and the way it was administered, is representative of the typical school situation. To make the aircraft noise more representative to the typical indoor environment, the sound was transformed as if travelled through a brick wall. On the other hand, the participants in the present investigation were constantly exposed to aircraft noise (or speech) during the reading phase of the prose memory task. This substantial exposure clearly exaggerates the amount of noise most school pupils are exposed to during such a limited amount of time. The merit of the present investigation is therefore mainly to have detected a relationship between WMC and distraction from aircraft noise. Future investigations, in particular those of chronic noise exposure, should include measures of WMC to firmly establish the link between WMC and susceptibility to noise effects in more ecological situations.

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Abstract

Serial short-term memory is impaired by background sound, at least when a sound element suddenly deviates from an otherwise repetitive sequences (the deviation effect) and when each sound element in the sequence differs from the preceding one (the changing-state effect). Two competing theories have been proposed to explain these effects: one suggesting that both effects are caused by the same mechanism (i.e., attentional resources being depleted by the sound), the other suggesting that the deviation effect is caused by attentional capture and that the changing-state effect is caused by interference between order processes. The present investigation found that working memory capacity predicts susceptibility to the deviation effect but not to the changing-state effect, both when speech items (Experiment 1) and when tones (Experiment 2) produce the disruption. These results suggest that the two effects are caused by different mechanisms and support the duplex-mechanism account of auditory distraction.

Keywords: auditory distraction, attentional capture, changing-state effect, deviation effect, working memory capacity
As is well known, serial short-term memory of visually presented items is impaired by the mere presence of background sounds (Colle & Welsh, 1976; Ellermeier & Zimmer, 1997; Jones & Macken, 1993; Macken, Tremblay, Alford, & Jones, 1999; Salamé & Baddeley, 1982), at least when the sound sequence changes acoustically. For instance, the sound sequence “k l m v r q c” is more distracting to serial recall than is the sound sequence “c c c c c c c”. This finding is called the changing-state effect (Jones & Macken, 1993; Macken et al., 1999). Furthermore, an auditory event that stands out or deviates from the recent auditory past, such as the sound “m” in the sound sequence “c c c m c c c”, disrupts serial recall. This phenomenon is known as the deviation effect (Hughes, Vachon, & Jones, 2005, 2007; Lange, 2005; see also Parmentier, 2008).

The interference-by-process account has been proposed as a possible explanation to the changing-state effect (Macken et al., 1999). According to this theory, the changing-state effect is caused by interference between two sets of order processes: the automatic processing of order between successive and perceptually discrete sound events and the deliberate processing of the order between the to-be-serially recalled items. Based on this theory then, the changing-state effect only takes place when the primary task requires order processing (e.g., serial rehearsal of visual-verbal items). Cowan (1995) has proposed another possibility. According to his theory, changes in a sound stream deplete attentional resources which could otherwise be used to entertain the focal task. In other words, each new sound element in a changing-state sound stream (e.g., “k l m v r q c”) attracts orienting responses (Öhman, 1979; Siddle, 1991; Sokolov, 1963) that is accompanied by a redirection of attention towards the new stimulus, away from the focal task, and causes disruption. The same mechanism could also explain the deviation effect: the sound element “m” in the sound sequence “c c c m c c c” elicits an orienting response and disrupts performance as a consequence. Cowan’s theory is attractive due to its parsimonious character, and at first
glance it may seem like a changing-state sound sequence is just a series of deviant sounds in that each item deviates from the preceding item. However, a number of findings suggest that changing-state and deviating sounds have different effects on cognitive performance: first, a deviating sound disrupts performance on tasks that do not require any order processing (e.g., Berti & Schröger, 2003; Hughes et al., 2007; Parmentier, 2008) but changing-state sound sequences do not (Hughes et al., 2007; Jones & Macken, 1993; Perham, Banbury, & Jones, 2007); second, the changing-state effect and the deviation effect do not interact in their disruption of serial recall (Hughes et al., 2007); third, the deviation effect is absent when the deviant is presented during a retention interval between encoding and retrieval, whereas the changing-state effect is still present when the sound is presented during the retention interval (Hughes et al., 2005); and fourth, a large body of evidence have demonstrated habituation towards the disruptive effects of deviating sounds on task performance (e.g., Debener, Kranczioch, Herrmann, & Engel, 2002; Friedman, Cycowicz, & Gaeta, 2001; Siddle, 1991; Sokolov, 1963), but people seem unable to habituate to the effects of changing-state sound sequences on serial recall (Ellermeier & Zimmer, 1997; Jones, Macken, & Mosdell, 1997; Tremblay & Jones, 1998). These results lean towards the possibility that the changing-state effect and the deviation effect are caused by qualitatively different mechanisms. Because of this, Hughes et al. (2007) proposed a duplex-mechanism account of auditory distraction. According to this view, the changing-state effect is the result of interference between order processes whereas the deviation effect is caused by attentional capture. The purpose of the present study was to investigate the nature of the mechanisms that underlie individual differences in susceptibility to these two effects.

Complex span tasks are typically employed to investigate individual differences in cognitive capacity. In a classic complex span task called “operation span” (OSPAN) the participants are presented with sets of operation-word strings (e.g., “Is \(4 \times 3\) + 5 = 17?
CACTUS”) and requested to respond “yes” or “no” to the operation and to remember the word for later recall. After responding to a set of those operation-word strings, the participants recall the words. The score on the recall-part of the task is used to measure what is called working memory capacity (WMC). A large number of studies have shown that WMC is extremely successful in predicting performance across a wide range of domains (for reviews, see Engle, 2002; Unsworth & Engle, 2007) including the anti-saccade task (Kane, Bleckley, Conway, & Engle, 2001; Unsworth, Schrock, & Engle, 2004), Eriksen’s flanker task (Heitz & Engle, 2007), the attention network test (Redick & Engle, 2006), and the Stroop task (Kane & Engle, 2003). Findings such as these have led some authors to argue that WMC measures individual differences in a general and limited pool of attentional resources that can be used to inhibit task-irrelevant information and constrain attention to the primary task (Engle, 2002; Kane et al., 2001; Lustig, Hasher, & Zacks, 2008).

If the changing-state effect is caused by depletion of attentional resources, as suggested by Cowan (1995), there should be a relationship between WMC and the magnitude of the changing-state effect. However, several authors have tried, but failed, to find this relationship (Beaman, 2004; Elliott & Cowan, 2005; see Elliott, Barriileaux, & Cowan, 2006 for an exception). On the other hand, if the changing-state effect is caused by interference between order processes, as proposed by the interference-by-process account (Macken et al., 1999), then individual differences in the capability to process order should predict disruption rather than WMC. To support this claim, Macken, Phelps and Jones (2009) presented participants with pairs of sound-patterns and requested them to judge whether or not the two patterns in each pair were the same. The authors argued that the pattern-matching task measures the capability to automatically process order information in sound sequences, and they were able to show that the participants who performed well on the pattern-matching task were the ones most susceptible to the changing-state effect. The authors concluded that the
magnitude of the changing-state effect is a function of the efficiency by which people process the order between individual sound elements, not a function of an all-purpose pool of attentional resources (i.e., WMC).

In contrast to those studies, a handful of experiments have shown that WMC does indeed predict susceptibility to some types of auditory distraction not evidently dependent on a conflict between order processes. For instance, Beaman (2004) requested participants to view lists of visual to-be-remembered words (e.g., tools) with the task to recall the words in free order, and thereafter he presented lists of to-be-ignored speech words that were semantically related to the to-be-remembered words (e.g., other tools). At recall, low-WMC individuals reported more of the to-be-ignored speech words than high-WMC individuals did. Other studies have shown that people with high WMC are less susceptible to the detrimental effects of speech and aircraft noise on reading comprehension and prose memory (Sörqvist, in press; Sörqvist, Halin, & Hygge, 2010; Sörqvist, Ljungberg, & Ljung, in press). Besides these demonstrations of relationships between WMC and auditory distraction, a study by Conway, Cowan and Bunting (2001) is particularly interesting to the present investigation. When engaged in a conversation at a party, hearing our own name spoken in the background can capture our attention (i.e., the “cocktail party phenomenon”). Conway et al. investigated the role of WMC in this phenomenon by requesting participants to continuously repeat aloud (i.e., shadow) a message presented to one ear while ignoring another message presented to the other ear. The participant’s own name was spoken in the to-be-ignored message at some point during shadowing. The results revealed that high-WMC individuals were less likely to report hearing their own name. Furthermore, they were less likely to make shadowing mistakes when their name was presented. Since the deviation effect seems to be a result of attentional capture (e.g., Hughes et al., 2007) similar to the cocktail
party phenomenon, Conway et al.’s results suggest that WMC should predict the magnitude of the deviation effect.

The possibilities that susceptibility to the changing-state effect is a function of order processes (Macken et al., 2009) and that susceptibility to the cocktail party phenomenon is a function of WMC (Conway et al., 2001) fit nicely with the duplex-mechanism account of auditory distraction (Hughes et al., 2007). To recollect, this account proposes that the deviation effect is caused by attentional capture, and if WMC reflects some general pool of attentional resources (e.g., Kane et al., 2001), then high WMC should attenuate the deviation effect. In contrast, WMC should not predict the magnitude of the changing-state effect because this effect is caused by interference between order processes. The present investigation tested these hypotheses in two experiments. In Experiment 1, the disruption of serial recall was produced by speech sounds. In Experiment 2, the disruption was produced by tones to test if the same pattern of results would generalize across speech and non-speech sounds.

Experiment 1
Method
Participants
A total of 40 university students (mean age = 23.35 years, SD = 5.27) participated in Experiment 1 in exchange for a small honorarium. They all reported normal hearing, normal or corrected-to-normal vision and Swedish as their native tongue.

Apparatus and materials

Operation span. A computerized version of the operation span task developed by Turner and Engle (1989) was adopted. In this task, mathematical operations such as “IS (6 +
were presented on a computer screen. The participants’ were requested to answer “yes” or “no” to the question by pressing a button on the keyboard. They were encouraged to respond as accurately and quickly as possible. After pressing the button, the screen went blank and then a one-syllable noun (e.g., CAT) was presented on the screen for one second, which the participants were told to remember for later recall. When the to-be-remembered word disappeared a new mathematical operation was presented or the list ended depending on the length of the list. The list length (i.e., the number of words to-be-remembered) varied between two and six. The words within a list were semantically unrelated, and each word was presented only once during the task. When the last word in each list had been presented, the participants were instructed to recall as many of the words as they could remember in the order of presentation by typing on the computer keyboard. The total number of lists was 16 (i.e., three of each list length and one list for practice) and the lists were presented in the same random order for each participant. The task was scored using a proportion procedure (see Conway, Kane, Bunting, Hambrick, Wilhelm, & Engle, 2005) in which each word recalled in the correct serial position was given credit. The total number of words accurately recalled in each list respectively was then divided by the list-length. For instance, if the participants recalled all four words in the correct serial position on a four-word list, they would receive one point for that list, but if four out of five words were recalled on a five-word list they would receive 0.80 points for that list. These proportions were thereafter averaged over the total number of lists (i.e., 15).

Serial recall. The to-be-remembered visually presented sequences consisted of eight digits taken without replacement from the set 1-9. They were arranged in a pseudo-random order (successive digits were not arithmetically adjacent). Each digit was presented for 350 ms with an inter-stimulus interval of 400 ms (similar to Hughes et al., 2007).
A set of four spoken letters ("c, k, m, j") was recorded in an even-pitched male voice, with Swedish pronunciation, and sampled with a 32-bit resolution, at a sampling rate of 44.1 KHz. The spoken items were digitally edited to last 200 ms in length. Three types of task-irrelevant sound sequences were composed from this set of spoken letters using computer software. In a steady-state sequence, the spoken letter "c" was presented 21 times. Each item was separated by a 100 ms silent pause. A deviant sequence was identical to a steady-state sequence with the exception that the 11th item was the spoken letter "k" instead of "c". A changing-state sequence was identical to a steady-state sequence, except that it consisted of 21 spoken letters taken from the set of four and repeated systematically ("c, k, m, j, c, k, m, j, c" and so on). The onset of the first spoken letter, identical for all three types of sound sequences, occurred 300 ms before the first to-be-remembered digit. The 11th spoken letter was presented in-between the fourth and the fifth to-be-remembered digit and the final spoken letter was presented 100 ms after the eighth to-be-remembered digit.

The participants were asked to recall the digits in order of presentation 500 ms after the final spoken letter had been presented. The participants were instructed to always recall eight digits, to make sure to place the digits in the correct serial position, and to guess if they did not know which digit should be where in the sequence. Recall was self-paced and made by typing with the computer keyboard. When the participants had recalled the digits, they pressed a button that automatically initiated the next trial.

**Design and procedure**

A within-subjects design was used. The participants were tested individually in a sound-attenuated room. The presentation of test materials was made by a computer and the sound (with 32-bit resolution and 44,100 Hz sampling rate, at approximately 65 dB[A] as measured by a Brüel & Kjaer sound level meter) was played through headphones (Sennheiser HD 202).
attached to the computer (with a Soundmax Digital HD Audio soundcard). The participants were instructed to ignore any sound they would hear in the headphones. All participants began with performing the operation span task. Thereafter, they performed two blocks of 30 serial recall trials. In one block (called the deviant block), the first two trials were steady-state trials and used to familiarize the participants with the task. Performance on these trials was excluded from the analysis. The remaining 28 trials consisted of 22 steady-state trials and 6 deviant trials. The deviant trials occurred at trial number 5, 9, 15, 21, 24 and 29. The other block (called the changing-state block), was identical to the deviant block, with the exception that changing-state sound sequences were played instead of deviant sound sequences at trial number 5, 9, 15, 21, 24 and 29. The two blocks were separated by a self-paced pause and the order of the two blocks was counterbalanced between participants (half began with the deviant block and the other half began with the changing-state block). The experimental session lasted for approximately 30 minutes.

Results

Operation span

The participants’ mean score on the OSPAN task (in proportion) was .76 (SD = .14, range .41-.97). The mean score on the operation-part of the task (in proportion) was .92 (SD = .06, range .77-1.00). A correlation analysis revealed a positive and significant correlation between OSPAN score and operation performance, \( r(38) = .32, p < .05 \). This is fortunate because it indicates that the participants who scored high on the memory-part of the task didn’t do so because they skipped the operation-part of the task.

Serial recall
The responses on the serial recall task were scored according to a strict serial recall criterion (points were given only to correct items placed in the correct serial position). Since there were more steady-state trials than other types of trials, the score was calculated as the percentage of digits correctly recalled within each sound condition and type of block (deviant or changing-state) respectively.

**The deviant block:** In this section, the data were taken only from the deviant block. As can be seen in Figure 1, the deviant reduced recall across most serial positions. A 2 (background condition: steady-state vs. deviant) × 8 (serial position) analysis of variance revealed a significant main effect of background condition, $F(1, 39) = 47.26, MSE = 0.04, p < .001, \eta^2 = .55$, and of serial position, $F(7, 273) = 34.01, MSE = 0.05, p < .001, \eta^2 = .47$, and a significant interaction between the two variables, $F(7, 273) = 4.08, MSE = 0.02, p < .01, \eta^2 = .10$.

The common way to measure individual differences in susceptibility to auditory distraction is to take the difference between the score in the control condition and the distraction condition (Ellermeier & Zimmer, 1997; Macken et al., 2009). This method was therefore used here as well. The mean difference-score was 0.11 ($SD = 0.10$). The correlation between OSPAN scores and the difference-scores was significant and negative, $r(38) = -.35, p < .05$, which indicates that high WMC attenuates the deviation effect. This relationship is illustrated in Figure 2. There is reason to believe that using difference-scores is a less sophisticated statistical analysis than using residual analysis because the error measurement of difference-scores is larger than the error of residuals (Cronbach & Furby, 1970). Therefore, a hierarchal regression analysis with scores in the deviant condition as dependent variable, scores in the steady-state condition as independent variable in the first step and OSPAN scores as independent variable in the second step was calculated. The analysis revealed a significant regression model in the first step, $R^2 = .70, F(1, 38) = 89.65, MSE = 0.01, p < .001,$
and in the second step, $R^2 = .77$, $F(2, 37) = 60.48$, $MSE = 0.01$, $p < .001$. The scores in the steady-state condition explained a significant part of the variance, $\beta = .73$, $t = 8.49$, $p < .001$ (in the second step of the analysis), and OSPAN score explained a significant part of the residual variance not explained by the scores in the steady-state condition, $\beta = .27$, $t = 3.17$, $p < .005$. The residual analysis is therefore consistent with the analysis based on difference scores: high WMC attenuates the deviation effect.

The changing-state block. In this section, the data were taken only from the changing-state block. As can be seen in Figure 1, the changing-state effect was replicated. A 2 (background condition: steady-state vs. changing-state) $\times$ 8 (serial position) analysis of variance revealed a significant main effect of background condition, $F(1, 39) = 57.61$, $MSE = 0.04$, $p < .001$, $\eta^2 = .60$, and of serial position, $F(7, 273) = 48.44$, $MSE = 0.05$, $p < .001$, $\eta^2 = .55$, and a significant interaction between the variables, $F(7, 273) = 2.57$, $MSE = 0.02$, $p < .05$, $\eta^2 = .06$.

To obtain a measure of individual differences in susceptibility to the changing-state effect, the difference between the scores in the steady-state condition and the scores in the changing-state condition was calculated. The mean difference-score was 0.13 ($SD = 0.11$). The correlation between OSPAN scores and the difference-scores was negative but non-significant, $r(38) = -.14, p = .40$. Hence, there is no evidence of a relationship between WMC and the changing-state effect. Following the advice by Cronbach and Furby (1970), a hierarchal regression analysis with scores in the changing-state condition as dependent variable, scores in the steady-state condition as independent variable in the first step and OSPAN score as independent variable in the second step was calculated. The analysis
revealed a significant regression model in the first step, $R^2 = .64$, $F(1, 38) = 68.67$, $MSE = 0.01$, $p < .001$, and in the second step, $R^2 = .67$, $F(2, 37) = 37.13$, $MSE = 0.01$, $p < .001$. The scores in the steady-state condition explained a significant part of the variance, $\beta = .74$, $t = 7.13$, $p < .001$ (in the second step), but OSPAN score did not explain a significant part of the residual variance, $\beta = .17$, $t = 1.62$, $p = .11$. The regression analysis is hence consistent with the analysis using difference scores: no evidence of a relationship between WMC and the changing-state effect could be revealed.

Discussion

The results of Experiment 1 indicate that high WMC attenuates the deviation effect but not the changing-state effect. Even though the difference-scores analysis clearly proposes that WMC is unrelated to the changing-state effect, the residual analysis points towards the possibility that WMC could be related to the changing-state effect provided enough statistical power, even though this relationship should be much weaker than the relationship between WMC and the deviation effect. Furthermore, previous studies indicate that WMC might be related to the changing-state effect when produced by tone sequences rather than spoken-letter sequences (Elliott et al., 2006). Because of this, Experiment 2 intended to test if the pattern of results found in Experiment 1 replicates when tone sequences produce the disruption.

Experiment 2

Method

Participants

A total of 48 university students (mean age = 24.46 years, $SD = 3.90$) participated in Experiment 2 in exchange for a small honorarium. They all reported normal hearing, normal
or corrected-to-normal vision and Swedish as their native language. None participated in Experiment 1.

Apparatus and materials
The materials were identical to those of Experiment 1 except for the sound sequences. In Experiment 2, three types of tone sequences were generated with a computer software programme. In a steady-state sequence, 21 tones were presented. The tones were played at 440 Hz, were 200 ms in length (with 10 ms rise and fall time) and separated by a 100 ms silent pause. A deviant sequence was identical to a steady-state sequence with the exception that the 11th tone was played at 220 Hz instead of 440 Hz. A changing-state sequence was identical to a steady-state sequence, except that it consisted of 21 tones taken from a set of four (“220 Hz, 440 Hz, 880 Hz, 1760 Hz”) and repeated systematically (“440 Hz, 880 Hz, 220 Hz, 1760 Hz, 440 Hz, 880 Hz”, and so on).

Design and procedure
The design, procedure, and when and how the sound sequences were presented were identical to Experiment 1.

Results
Operation span
The participants’ mean score on the OSPAN task (in proportion) was .79 (SD = .15, range .40-.99). The mean score on the operation-part of the task (in proportion) was .94 (SD = .05, range .80-1.00). A correlation analysis revealed a positive and significant correlation between OSPAN score and operation performance, $r(46) = .28, p = .05$. Hence, as in Experiment 1, the
participants who scored high on the memory-part of the task didn’t do so because they skipped the operation-part of the task.

**Serial recall**

The serial recall task was scored the same way as in Experiment 1.

**The deviant block.** In this section, the data were taken only from the deviant block. As can be seen in Figure 3, the deviation effect was replicated. A 2 (background condition: steady-state vs. deviant) × 8 (serial position) analysis of variance revealed a significant main effect of background condition, $F(1, 47) = 12.95$, $MSE = 0.04$, $p < .001$, $\eta^2 = .22$, and of serial position, $F(7, 329) = 25.73$, $MSE = 0.06$, $p < .0001$, $\eta^2 = .35$, and a significant interaction between the two variables, $F(7, 329) = 4.04$, $MSE = 0.02$, $p < .001$, $\eta^2 = .08$.

The mean difference-score between the steady-state condition and the deviation condition was 0.05 ($SD = 0.10$). The correlation between OSPAN scores and the difference-scores was significant and negative, $r(46) = -.31$, $p < .05$, which indicates that high WMC attenuates the deviation effect. This relationship is illustrated in Figure 4. The difference-score analysis was complemented by a hierarchical regression analysis following statistical advice by Cronbach and Furby (1970). Scores in the deviant condition was dependent variable in this analysis, scores in the steady-state condition was independent variable in the first step and OSPAN score was independent variable in the second step. The regression model was significant in the first step, $R^2 = .76$, $F(1, 46) = 143.75$, $MSE = 0.01$, $p < .01$, and in the second step, $R^2 = .79$, $F(2, 45) = 84.91$, $MSE = 0.01$, $p < .01$. The scores in the steady-state condition explained a significant part of the variance, $\beta = .79$, $t = 10.32$, $p < .01$ (in the second step of the analysis), and OSPAN score explained a significant part of the residual variance not explained by the scores in the steady-state condition, $\beta = .20$, $t = 2.57$, $p < .05$. The
residual analysis is therefore consistent with the analysis based on difference scores: high-WMC individuals are less susceptible to the deviation effect.

The changing-state block. In this section, the data were taken only from the changing-state block. As can be seen in Figure 3, the changing-state effect was replicated once more. A 2 (background condition: steady-state vs. changing-state) × 8 (serial position) analysis of variance revealed a significant main effect of background condition, $F(1, 47) = 13.41, MSE = 0.05, p < .001, \eta^2 = .22,$ and of serial position, $F(7, 329) = 18.01, MSE = 0.07, p < .0001, \eta^2 = .28,$ and the interaction between the variables approached significance, $F(7, 329) = 1.88, MSE = 0.02, p = .07, \eta^2 = .04.$

The mean difference-score between the steady-state condition and the changing-state condition was 0.06 ($SD = 0.11$). The correlation between OSPAN scores and the difference-scores was positive but non-significant, $r(46) = .19, p = .20.$ Hence, there was no evidence of a relationship between WMC and the changing-state effect. If anything, the correlation analysis indicates that high-WMC individuals are slightly, but far from significantly, more susceptible to the changing-state effect. Following the advice by Cronbach and Furby (1970), a hierarchal regression analysis with scores in the changing-state condition as dependent variable, scores in the steady-state condition as independent variable in the first step and OSPAN scores as independent variable in the second step was calculated. The analysis revealed a significant regression model in the first step, $R^2 = .66, F(1, 46) = 90.89, MSE = 0.01, p < .01,$ and in the second step, $R^2 = .67, F(2, 45) = 46.04, MSE = 0.01, p < .01.$ The scores in the steady-state condition explained a significant part of the variance, $\beta = .87,$ $t$
Discussion

Experiment 2 replicated the relationship between WMC and the deviation effect found in Experiment 1. Furthermore, WMC was once again unrelated to the changing-state effect. In fact, in Experiment 2 the relationship between WMC and the deviation effect differed significantly from the relationship between WMC and the changing-state effect ($r = -.31$ and $r = .19$, respectively, $t[45] = 3.02, p < .01$), which provides relatively strong evidence for the assumption that the two effects are produced by different mechanisms.

General Discussion

The investigation reported here is the first to demonstrate a relationship between working memory capacity (WMC) and the deviation effect. This finding accords with previous studies showing that high WMC can attenuate the power of sounds to capture attention (Conway et al., 2001). The experiments reported here also found that WMC is unrelated to the changing-state effect, consistent with previous research (Beaman, 2004; Elliott & Cowan, 2005). This pattern of results was the same whether spoken letters (Experiment 1) or tones (Experiment 2) constituted the sound sequences that produced the disruption of the serial recall task.

Based on the results reported here, it seems safe to conclude that at least two mechanisms underlie individual differences in susceptibility to auditory distraction. One of those mechanisms is measured by WMC and contributes to several auditory distraction phenomena (Beaman, 2004; Conway et al., 2001; Sörqvist, in press; Sörqvist et al., in press; Sörqvist et al., 2010) including the deviation effect. The other mechanism is the efficiency by which people process the order between successive and perceptually discrete sound events,
which contributes to individual differences in susceptibility to the changing-state effect (Macken et al., 2009). The observation that two different mechanisms underlie the deviation effect and the changing-state effect is especially supportive of the duplex-mechanism account by Hughes et al. (2007) according to which the two effects have qualitatively different origins. Altogether, the results suggest that the changing-state effect is caused by interference between order processes, whereas the deviation effect is caused by some mechanism related to attention switching. Yet, there are alternative interpretations of the results reported here that should be addressed. For instance, it could be argued that high-WMC individuals can control attention switching towards deviating sounds as long as the degree of deviation is relatively small (as with sound sequences that includes a single deviant). A changing-state sound sequence, however, involves so much acoustic change that it breaks through high-WMC individuals’ capability to control the orienting responses towards the sounds. In other words, the deviation effect and the changing-state effect may differ only to the degree they capture attention, not in quality. This could explain the absences of a relationship between WMC and the changing-state effect and would be consistent with theories assuming similar mechanisms for both effects (cf. Cowan, 1995). However, there are a number of reasons to doubt this alternative interpretation. Hughes et al. (2005, 2007) have shown that deviating sounds and changing-state sounds have qualitatively different effects on cognitive performance. In addition to their findings, the present investigation shows that the magnitude of the two effects is approximately equal (see Figure 1 and Figure 3). If the two effects would be produced by the same mechanism, the changing-state sound sequences should have caused a substantially larger degree of disruption.

It should be noted that Elliott et al. (2006) found high-WMC individuals to be less susceptible to the changing-state effect when it was produced by tone sequences. However, there are reasons to question if this finding is a relationship between WMC and the
classic changing-state effect. First, the authors failed to find a similar relationship with spoken-letter sequences in the same experiment. This is alarming because a large body of evidence suggest that tone sequences and spoken-letter sequences produce qualitatively equal (changing-state) effects on serial recall (e.g., Jones & Macken, 1993; Tremblay, Nicholls, Alford, & Jones, 2000; for a review, see Macken et al., 1999). Second, a handful of experiments have failed to find relationships between memory capacity and the changing-state effect (Beaman, 2004; Ellermeier & Zimmer, 1997; Neath, Farley, & Surprenant, 2003), including the experiments reported here and an experiment (Elliott & Cowan, 2005) using the exact same tone sequences as those used by Elliott et al.. Furthermore, if the deviation effect and the changing-state effect are indeed caused by a mechanism related to WMC, it is difficult to see why the investigation reported here indicates that the relationship between WMC and the deviation effect is significantly different from the relationship between WMC and the changing-state effect. Taken together, the weight of evidence supports that WMC is not related to the changing-state effect.

Another contribution from the present investigation is worth highlighting. Previous studies of the deviation effect in short-term memory have used speech sounds to produce the disruption (Hughes et al., 2005, 2007). The present study extends the deviation effect in short-term memory to non-speech sounds (but see Lange, 2005, for a slightly different way of producing the deviation effect with non-speech sounds). This result is not surprising because deviation effects have been produced with non-speech sounds in other paradigms (e.g., Berti & Schröger, 2003; Parmentier, 2008). Yet, the results are important because they make the phenomenon difficult for theories trying to explain auditory distraction of short-term memory in terms of the structural similarity between the content of the task-relevant materials and the task-irrelevant materials (e.g., Neath, 2000; Salamé & Baddeley,
Since verbal memory materials and tones have fairly little content in common, those theories can hardly explain why deviating tones disrupt serial-verbal short-term memory.

Finally, I turn to the implications of the results presented here to the nature of WMC. In a recent review of the WMC literature, Unsworth and Engle (2007) concluded that individual differences in WMC reflect differences in two mechanisms: (a) the ability to retrieve items from secondary memory, and (b) to actively maintain items in primary memory in the presence of interference. This conceptualization of WMC is consistent with the older views of WMC as essentially being a measure of domain-general attentional control and resistance to interference (Cowan, 2005; Engle, 2002; Kane et al., 2001; Lustig et al., 2008).

The relationship between WMC and the deviation effect can be explained by high-WMC individuals being more efficient in retrieving the target items from secondary memory when attention has been diverted by the deviant. However, the proposition that WMC also reflects a general capability to resist interference is faced by several problems from the results reported here. First, parts of the relationship between WMC and the deviation effect seem to have arisen due to high-WMC individuals performing slightly better in the presence of the deviant (see Figure 2 and Figure 4). Hence, high-WMC individuals seem not simply better able to resist interference. It seems plausible that high-WMC individuals are more efficient in the capability to inhibit the act of diverting attention when a deviant is presented, and this inhibition process could be accompanied with increased activation of target items. Another possibility is that a deviant increases high-WMC individuals’ arousal and their capability to focus on the target items increases as a consequence, a view which would be consistent with some other studies of positive effects of noise on cognitive performance (Sikström & Söderlund, 2007). Another problem faced by the view of WMC as resistance to interference is the absence of a relationship between WMC and the changing-state effect. The results seem to indicate that WMC more specifically measures a capability to control “attention switching”
(cf. Berti & Schröger, 2003; Lavie & de Fockert, 2005) and perhaps retrieval of items from secondary memory (Unsworth & Engle, 2007), not a domain-general resistance to interference or some other all-purpose pool of attentional resources (cf. Sörqvist et al., in press).
References


Author note

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Figure Captions

Figure 1. Mean percentage of items correctly recalled in each serial position in the steady-state condition in the deviant block (SS-DB), the steady-state condition in the changing-state block (SS-CSB), the deviant condition (D) and the changing-state condition (CS) in Experiment 1. Error bars show standard errors of mean.

Figure 2. The correlation between operation span score and the deviation effect (calculated as the difference between serial recall score in the steady-state condition and serial recall score in the deviant condition) in Experiment 1.

Figure 3. Mean percentage of items correctly recalled in each serial position in the steady-state condition in the deviant block (SS-DB), the steady-state condition in the changing-state block (SS-CSB), the deviant condition (D) and the changing-state condition (CS) in Experiment 2. Error bars show standard errors of mean.

Figure 4. The correlation between operation span score and the deviation effect (calculated as the difference between serial recall score in the steady-state condition and serial recall score in the deviant condition) in Experiment 2.
Figure 1

% correct

Serial position
Figure 2

![Graph showing the relationship between Deviation effect and Operation span score. The graph displays a scatter plot with a negative linear trend.]
Figure 3

![Graph showing serial position effect with different conditions: SS-DB, SS-CSB, D, CS. The x-axis represents serial position (1 to 8), and the y-axis represents percentage correct. The graph demonstrates a decline in correct responses as the serial position increases.](image-url)
Figure 4

![Graph showing the relationship between Deviation effect and Operation span score. The graph displays a scatter plot with a downward trend line, indicating a negative correlation.]