

Running head: Working memory and auditory selective attention

The role of working memory in auditory selective attention

Polly Dalton¹, Valerio Santangelo^{2 3}, & Charles Spence⁴

¹ Department of Psychology, Royal Holloway, University of London, UK

² Department of Human and Educational Sciences, University of Perugia, Italy

³ Neuroimaging Laboratory, Santa Lucia Foundation, Rome, Italy

⁴ Department of Experimental Psychology, University of Oxford, UK

Address correspondence to:

Polly Dalton, Department of Psychology,

Royal Holloway, University of London,

Egham, Surrey, TW20 0EX, UK.

Email: polly.dalton@rhul.ac.uk

Tel: (44) 1784 443516

Abstract

A growing body of research now demonstrates that working memory plays an important role in controlling the extent to which irrelevant visual distractors are processed during visual selective attention tasks (e.g., Lavie et al., 2004). Recently, it has been shown that the successful selection of tactile information also depends on the availability of working memory (Dalton et al., in press). Here, we investigate whether working memory also plays a role in auditory selective attention. Participants focused their attention on short continuous bursts of white noise (targets) while attempting to ignore pulsed bursts of noise (distractors). Distractor interference in this auditory task, as measured in terms of the difference in performance between congruent and incongruent distractor trials, increased significantly under high (vs. low) load in a concurrent working memory task. These results provide the first evidence demonstrating a causal role for working memory in reducing interference by irrelevant auditory distractors.

The ability to select and attend to relevant auditory information at the expense of less relevant information has been the focus of a large body of research over the last 60 years. Much of the early debate concerned the stage at which distractors are eliminated from processing, with some researchers arguing that this occurred at an early stage of information processing, and others arguing that distractors were processed more thoroughly before being rejected (see Driver, 2001, for a review).

More recently, researchers have come to view distractor rejection as a variable process, in which distractors can be eliminated at an early stage of processing under certain conditions, but at a later stage under others. For example, many studies have now demonstrated that visual distractors are ignored more effectively when the visual target task is more perceptually demanding than when it is less demanding (see Lavie, 2005, for a review). In addition, research has demonstrated that visual distractor interference is more pronounced when participants are engaged in a concurrent task that places large demands on working memory (WM) as compared with a concurrent task involving lower WM demands. For example, Lavie et al. (2004) presented participants with a target letter (X or Z) along with a distractor letter which could be either congruent with respect to the target (e.g., an X when the target was X) or incongruent (e.g., a Z when the target was X). Participants had to respond to the identity of the target letters while ignoring the distractor letters as far as possible. Distractor interference was measured in terms of the difference in performance between congruent and incongruent trials. As they carried out the visual letter task, participants had to remember either a series of six randomly selected digits (the high WM load condition) or a single digit (the low load condition). The critical finding was that the irrelevant visual distractors interfered more with visual

target performance under conditions of high WM load than under low load conditions. Thus, the reduced availability of WM for the attention task under high (vs. low) WM load led to an increase in distractor interference under those conditions. These findings have now been replicated using several different visual attention tasks (e.g., De Fockert et al., 2001; Lavie & de Fockert, 2005). Researchers have thus proposed that the availability of WM is important for minimizing interference by task-irrelevant distractors, presumably through the active maintenance of current stimulus-processing priorities (Lavie, 2005).

Until recently, these findings had only been demonstrated within the visual modality. However, one very recent study has shown that tactile distractor interference increases under high (vs. low) WM load (Dalton et al., in press). Here, we ask whether successful auditory selective attention also depends on the availability of WM resources. Indeed, previous research has suggested that WM might be important for successful auditory selection. For example, several studies have shown that WM load can influence distraction by task-irrelevant features of attended auditory stimuli (e.g. Berti & Schröger, 2003; Muller-Gass & Schröger, 2007). However, these experiments did not include separable target and distractor stimuli, but instead presented the distracting feature as a part of the attended target stimulus. As such, this research cannot inform us about the role of WM in determining the extent of processing of task-irrelevant distractor stimuli.

Studies using the dichotic listening paradigm have found that participants with lower WM capacities are more likely to notice their own name in the unattended stream than those participants with higher WM capacities (Conway et al., 2001). However, because these findings are correlational in nature, they cannot demonstrate a causal role for WM in auditory selective attention. In addition, there is evidence to suggest that the

correlations observed by Conway and his colleagues might only hold in situations where participants are required to ignore semantically meaningful information (i.e., their own names) and not in situations where the possible interference is non-semantic (see Beaman, 2004). In the present study, we manipulated WM load during the performance of a non-semantic auditory attention task, in order to achieve a more direct and general measure of the importance of WM for auditory selective attention.

Participants performed an auditory response competition task in which they had to respond to the elevation of a continuous white noise target while ignoring a pulsed white noise distractor presented at an elevation that was either congruent or incongruent with respect to that of the target. While performing this auditory task, participants had to keep in mind a set of six digits, either in random order (high WM load condition) or in ascending numerical order (low WM load condition(Note1)) until a memory probe appeared. If the availability of WM plays a role in the control of auditory selective attention, then a high (vs. low) WM load during performance of the auditory task should result in greater interference by the irrelevant auditory distractors.

Methods

Participants. Twenty right-handed participants (six female), aged between 18-35 years, received a £5 gift voucher in return for their participation in this study.

Apparatus and stimuli. Figure 1 shows the experimental set-up. Participants sat at a table at a viewing distance of 50cm from a computer screen. Auditory stimuli were presented from four loudspeakers, approximately 30cm in front of the screen, two to the left (25cm from the centre of the screen) and two to the right (also at 25cm). Each of these loudspeaker pairs consisted of one upper loudspeaker (roughly 22.5cm above the

participant's ear level) and one lower loudspeaker (roughly 22.5cm below ear level). The target consisted of the presentation of white noise from one of the four speakers for 350ms. The distractor consisted of three short bursts of the same signal, each lasting 50ms and separated by 100ms empty intervals (giving a total duration of 350ms). Participants responded by pressing one of the four buttons on the computer keyboard. Stimulus presentation and response collection were controlled by a PC running E-Prime (Psychology Software Tools, Inc., Pittsburgh, PA).

Design and procedure. Each trial started with a black fixation dot presented at the center of a white screen for 500ms. Six black digits were then presented for 1500ms, separated from each other by $.05^\circ$ of visual angle and centered at fixation. Each digit subtended a visual angle of $0.25^\circ \times 0.3^\circ$. These digits constituted the memory set and participants had to remember them for report at the end of the trial. In the low load blocks, the six digits 1-6 were always presented in ascending numerical order. In the high load blocks, six digits (taken from the digits 0-9) were presented in a different random order on each trial. Following the display of the memory set, a visual mask consisting of six '#' signs was presented for 200ms. There then followed a series of either two, three or four target displays, each consisting of a continuous auditory target accompanied by a pulsed distractor. The number of target displays was made unpredictable in order to introduce variability into the onset of the memory probe, with the aim of encouraging the participants to maintain the memory set more actively in mind (cf. de Fockert et al., 2001). Targets were equally likely to be presented from any of the loudspeakers. Participants made speeded elevation discrimination responses (high vs. low) regarding the elevation of each target (regardless of whether it was presented on the left or right). A

pulsed distractor was simultaneously presented to one of the loudspeakers on the opposite side of the set-up, either at the same elevation (congruent trial) or at the opposite elevation (incongruent trial). Response measurement began 50ms after the start of stimulus presentation (because this was the earliest time at which the target and distractor could be differentiated). The participants were instructed to respond as rapidly and accurately as possible. Half of the participants responded to the auditory targets with their left hand ('a' for an upper target, 'z' for a lower target), whereas the remaining participants responded to the auditory targets with their right hand ('k' for an upper target, 'm' for a lower target). A feedback screen was presented for 500ms after each auditory task, either following a response or after 5000ms if no response had been made. This consisted of a blank screen if the response was correct; the word incorrect (written in red); or the word missed (written in red) if no response had been detected. A 1000ms blank screen was then presented before the next auditory task (or the memory test). After the final auditory task, a warning screen was presented for 1000ms, containing the words MEMORY TEST. Next there followed two probe digits, presented one after the other from the centre of the screen for 500ms each. A centrally-presented question mark then cued participants to respond to the memory probe. The task was to report whether or not the two probe digits were presented in the same order as they had been presented in the initial memory set. Those participants who responded to auditory tasks with the left hand responded to memory tasks with the right hand ('k' for correct order, 'm' for reversed order). The other half of participants responded to the memory task with the left hand ('a' for correct order, 'z' for reversed order). A feedback screen identical to that used for the auditory task was also presented following the memory test.

Participants were given several examples of target and distractor stimuli, followed by eight practice auditory tasks without distractors and a further eight auditory trials with distractors. They were then given two short practice blocks of the entire task including the memory set, one of high WM load and one of low load. Next, four experimental blocks, two of high WM load and two of low load, were presented. Each experimental block included five trials containing two auditory target displays, six trials containing three auditory target displays, and five trials containing four auditory target displays, so that each block contained 48 auditory target displays in total. The order of presentation of the blocks was counterbalanced across participants so that half received the blocks in the order: low, high, high, low, and the other half received the blocks in the reverse order.

Results and Discussion

Working memory task

Responses in the WM task were slower under high load ($M=2106\text{ms}$) than under low load ($M=1539\text{ms}$, $t(19)=7.68$, $p<.01$). Participants also made more errors under high load ($M=13\%$) than under low load ($M=2\%$, $t(19)=6.11$, $p<.01$). Overall, performance on the WM task was significantly worse under high load than under low load conditions, confirming that the WM manipulation used here was successful. These findings are in line with those of Dalton et al. (in press) in which the same WM task was used.

Auditory task

When incorrect responses were made on the WM task, the associated auditory trials were ruled out of the auditory task analyses. In addition, trials in which incorrect responses were made on the auditory task were ruled out of the auditory RT analyses, as

were trials with RTs longer than 1800ms (2.9% of trials). Table 1 presents the mean error rates and RTs from Experiment 1 as a function of distractor congruence (congruent vs. incongruent) and WM load (high vs. low).

RTs. A two-way within-participants ANOVA using the factors of distractor congruency (congruent vs. incongruent) and WM load (high vs. low) revealed a significant main effect of congruency, $F(1,19)=17.86$, $MSE=2990.61$, $p<.01$. Performance was worse when the distractor was incongruent ($M=645$ ms) than when it was congruent ($M=593$ ms). This significant congruency effect confirms the effectiveness of the novel auditory response competition task used in this study.

There was also a significant main effect of WM load, $F(1,19)=16.55$, $MSE=10445.29$, $p<.01$, such that responses were faster in the low load blocks ($M=573$ ms) than in the high load blocks ($M=666$ ms). However, this main effect was modulated by an interaction between memory load and distractor congruency, $F(1,19)=4.64$, $MSE=1128.90$, $p<.05$, such that distractor interference (as measured in terms of the difference between performance on congruent vs. incongruent trials) was significantly more pronounced under high WM load (M effect=68ms) than under low load (M effect=36ms), see Table 1. Interestingly, the distractor effects were significant even under low WM load, $t(19)=3.02$, $p<.01$. However, the fact that distractor interference increased further under high WM load suggests that WM plays a significant role in the control of auditory selective attention.

We tested this conclusion further by conducting an additional analysis examining naturally-occurring differences in WM ability within our sample. We divided the participants into two groups using a median split based upon overall accuracy in the WM

task. The ten 'high accuracy' participants ($M=96\%$ correct) performed significantly more accurately on the WM task than the remaining 'low accuracy' participants ($M=89\%$ correct, $t(18)=4.14$, $p<.01$)(Note 2). The two groups showed significantly different patterns of performance on the auditory task. A three-way mixed-model ANOVA on the RT data from the auditory task using the within-participants factors of distractor congruency (congruent vs. incongruent) and WM load (high vs. low) and the between-participants factor of WM accuracy (high vs. low) identified a significant interaction between distractor congruency and WM accuracy. Participants in the low accuracy group showed significantly larger congruency effects (M effect= 77ms) than participants in the high accuracy group (M effect= 26ms , $F(1,18)=5.20$, $MSE=2449.18$, $p<.05$). Thus, despite the apparently small difference in WM performance between the two groups, participants with comparatively lower WM abilities were more susceptible to auditory distraction than those with higher WM abilities.

Interestingly, there was no overall main effect of WM accuracy ($F<1$), indicating that both groups performed comparably overall on the auditory task. The factor of WM accuracy did not interact with WM load ($F=1$) and there was no three-way interaction ($F<1$), suggesting that both groups showed the same overall pattern of smaller congruency effects under low WM load than under high load. Thus, the only way in which the two groups differed in their performance on the auditory task was that the relatively lower accuracy group showed larger congruency effects overall. This finding is in line with previous studies showing that WM capacity correlates with auditory distractibility (e.g., Conway et al., 2001) and converges with the previous RT analysis to

suggest that WM plays an important role in determining the effectiveness of selective auditory attention.

Errors. A similar ANOVA on the error data revealed a significant main effect of congruency, $F(1,19)=13.07$, $\underline{MSE}=.003$, $p<.01$. In line with the RT results, performance was worse on incongruent trials ($M=9\%$) than on congruent trials ($M=4\%$), again confirming the effectiveness of the auditory response competition paradigm used. There was also a main effect of WM load, $F(1,19)=4.71$, $\underline{MSE}=.001$, $p<.05$, indicating that the small difference in error rates between high load blocks ($M=6\%$) and low load blocks ($M=7\%$) was statistically reliable, however the two factors did not interact ($F<1$).

Overall, the experiment reported here demonstrates that distractor interference in an auditory response competition task is more pronounced under conditions of high WM load than under conditions of low load. This result implies that the availability of WM is important for the successful control of auditory attention. Previous correlational research (Conway et al., 2001), along with the additional analysis of group differences in the present study, indicate that WM capacity is related to levels of distractor interference in auditory attention tasks. However, the direct manipulation of WM load used in the present experiment allows for the first demonstration of a causal role for WM in reducing distraction by irrelevant stimuli during an auditory selective attention task.

Taken alongside earlier findings in vision (see Lavie, 2005, for review), touch (Dalton et al., in press), and audition (e.g. Conway et al., 2001; Muller-Gass & Schröger, 2007), the present research suggests that WM is important for successful selective attention regardless of the sensory modality of the task. This conclusion would fit with the proposal that the specific role of WM in selective attention is to keep the current task

priorities in mind (e.g., Lavie et al., 2004), as this type of function would seem likely to be modality-independent.

Because hearing is free of the spatial restrictions of the other senses (such that it can monitor for stimuli in all directions simultaneously, whereas the other senses must focus on more restricted areas of space), it is often thought of as an ‘early warning’ system that allows us to monitor for changes in the environment (e.g., Henneman, 1952). According to this view, auditory ‘distractors’, while irrelevant to the task at hand, might nevertheless provide important environmental information, and one might therefore expect auditory attention to be captured by auditory distractors regardless of the availability of WM. From this point of view, our finding that auditory distractor processing can be modulated by WM availability might perhaps seem surprising. However, recall that the distractors did in fact cause significant interference even under conditions of low WM load. Thus, in the present experiment, although auditory distractor interference was modulated to a certain extent in line with current task priorities, it did not appear to be subject to full cognitive control.

References

- Beaman, C. P. (2004). The irrelevant sound phenomenon revisited: What role for working memory capacity? Journal of Experimental Psychology: Learning, Memory & Cognition, *30*, 1106-1118.
- Berti, S., & Schroger, E. (2003). Working memory controls involuntary attention switching: Evidence from an auditory distraction paradigm. European Journal of Neuroscience, *17*, 1119-1122.
- Conway, A. R., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. Psychonomic Bulletin & Review, *8*, 331-335.
- Dalton, P., Lavie, N., & Spence, C. (2009). The role of working memory in tactile selective attention. Quarterly Journal of Experimental Psychology, *62*, 635-644.
- de Fockert, J. W., Rees, G., Frith, C. D., & Lavie, N. (2001). The role of working memory in visual selective attention. Science, *291*, 1803-1806.
- Driver, J. (2001). A selective review of selective attention research from the past century. British Journal of Psychology, *92*, 53-78.
- Henneman, R. H. (1952). Vision and audition as sensory channels for communication. Quarterly Journal of Speech, *38*, 161-166.
- Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. Journal of Experimental Psychology: Human Perception and Performance, *21*, 451-468.

- Lavie, N. (2005). Distracted and confused?: Selective attention under load. Trends in Cognitive Sciences, *9*, 75-82.
- Lavie, N., & de Fockert, J. (2005). The role of working memory in attentional capture. Psychonomic Bulletin & Review, *12*, 669-674.
- Lavie, N., Hirst, A., De Fockert, J. W., & Viding, E. (2004) Load theory of selective attention and cognitive control. Journal of Experimental Psychology: General, *133*, 339-354.
- Muller-Gass, A., & Schröger, E. (2007). Perceptual and cognitive task difficulty has differential effects on auditory distraction. Brain Research, *1136*, 169-177.

Author Notes

This research was supported by a Junior Research Fellowship to PD from St Anne's College, Oxford.

Correspondence concerning this article should be addressed to Polly Dalton, Department of Psychology, Royal Holloway University of London, Egham, Surrey, TW20 0EX, UK. Electronic mail may be sent to polly.dalton@rhul.ac.uk.

Footnotes

1. We acknowledge that the low load task of remembering digits in numerical order is likely to have imposed minimal demands on WM. This allowed us to achieve a strong manipulation of the availability of WM, in contrasting this low load task against the very demanding high load task. While it might be possible to argue that the low WM load task in fact imposes no WM load, we prefer to label the task 'low load' in order to reflect the fact that task sharing and response requirements were fully matched across both working memory tasks.
2. Although we have termed the two groups 'high' and 'low' accuracy for ease of description, note that the 'low accuracy' group actually performed at close to 90% correct.

Table 1

Averages of participants' mean RTs in ms (RT) with standard errors (SE) and mean error rates (%E) as a function of distractor congruence and working memory load.

Load	Distractor congruence					
	Congruent			Incongruent		
	RT	SE	%E	RT	SE	%E
Low	555	41	5	591	37	10
High	632	44	4	700	43	8

Figure caption

Figure 1. Schematic outline of the experimental set-up.

Figure 1

