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Reverberant Auditory Environments: The Effects of Multiple Echoes on Distraction by 'Irrelevant' Speech

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SUMMARY

Two experiments examine the effect on an immediate recall test of simulating a reverberant auditory environment in which auditory distracters in the form of speech are played to the participants (the 'irrelevant sound effect'). An echo-intensive environment simulated by the addition of reverberation to the speech reduced the extent of 'changes in state' in the irrelevant speech stream by smoothing the profile of the waveform. In both experiments, the reverberant auditory environment produced significantly smaller irrelevant sound distraction effects than an echo-free environment. Results are interpreted in terms of changing-state hypothesis, which states that acoustic content of irrelevant sound, rather than phonology or semantics, determines the extent of the irrelevant sound effect (ISE).

The use of virtual environments (VE) in psychology is now well-established. Studies of spatial navigation (Ruddle, Payne, & Jones, 1998), spatial memory (Ruddle, Payne, & Jones, 1999), perception for action (Wann & Rushton, 1995) and neuropsychological rehabilitation (Wann, Rushton, Smyth, & Jones, 1997) have all benefited from these VE techniques. Outwith psychological studies, VE is also used to recreate historic structures and locations that are physically inaccessible either for geographical reasons or because the original has been destroyed (Barceló, Forte, & Sanders, 2000). However, virtual auditory environments are much less common than virtual visual environments. When virtual auditory environments have been created, however, they have proved useful to the study of the 'sense of place' associated with particular buildings and historic sites and contributed to understanding of ancient rituals, producing a compelling feeling of immersion in the artificially produced world (e.g. Watson, 2001; Watson & Keating, 1999). The purpose of the current study is to apply similar techniques to the study of auditory distraction by so-called 'irrelevant sound' known to disrupt working memory.

The distracting effects of irrelevant sound on immediate memory are well-documented (Banbury, Tremblay, Macken, & Jones, 2001; Beaman, 2005a; Hughes & Jones, 2001, 2003). A number of authors have examined how the effect can be influenced by perceptually 'streaming' (Jones, Alford, Bridges, Tremblay, & Macken, 1999), individual susceptibility (Beaman, 2004; Ellermeier & Zimmer, 1997; Elliott & Cowan, 2005) or by

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habituation (Banbury & Berry, 1997; Jones, Macken, & Mosdell, 1997; Tremblay & Jones, 1998). The nature of the processing tasks affected by the irrelevant sound has also been considered (Banbury & Berry, 1998; Beaman, 2005a; Beaman & Jones, 1997, 1998; LeCompte, 1994), but few studies have examined how the acoustic environment, as opposed to the intended acoustic characteristics of the message, impacts upon the effect. Experimental techniques enabling the systematic manipulation of the acoustic characteristics of environment do, however, hold the potential to identify the type of environment in which auditory distraction is likely to be experienced without the need for *in situ* testing. This provides the experimenter with a carefully controlled manipulable environment.

PSYCHOPHYSICAL CHARACTERISTICS OF ECHO AND OF AUDITORY DISTRACTION

The acoustic signal as it reaches the ear is a function of the intended acoustics of the message and the moderating properties, or 'transfer function' of the environment, where the walls, furniture and physical characteristics of the room act as a filter, shaping the sound as it passes through. The same acoustic signal may appear in a very different form by the time it reaches the receiver (in this case the ears) to the way it appears as it leaves the transmitter (the vocal tract, in the case of speech). This is a problem for those individuals who wish to receive the message and may also be a problem for individuals adversely affected by certain characteristics of the sound—as it appears when it reaches them—who need not have any interest in the content of the message. Manufacturers now supply acoustic ceilings designed to reduce the echo experienced, particularly within larger offices or workplace environments, by absorbing rather than reflecting the sound. The design and marketing of acoustic ceilings, active noise cancellation headsets and similar devices is based upon the premise that reducing the noise in an environment is necessarily a positive move. While there may be good (e.g. aesthetic) reasons for wishing to reduce background noise, noise reduction might also be, in some situations, a backward step. For example, there have been anecdotal reports that active noise cancellation headsets, when used on commercial airliners, increase distraction because although engine noise is attenuated the conversations of other passengers are not. There are also good theoretical reasons to suppose that increasing reverberation, defined as multiple reflections of a signal bounced back from surfaces, might serve to reduce distraction due to task-irrelevant sound, the irrelevant sound effect (ISE; Beaman & Jones, 1997). This possibility is tested in the current study.

Although no general agreement has yet been reached concerning the exact nature and locus of the ISE (see Larsen & Baddeley, 2003; Neath, 2000 and accompanying commentaries), some empirical aspects of the effect are well-established. Specifically, the role of *changing-state* in the ISE (Jones, Madden, & Miles, 1992) is readily replicable. The changing-state effect refers to the finding that disruption to an immediate memory task is usually observed when the noise varies along some dimension (e.g. frequency or pitch) from one physically discrete event to another. Changing-state information contrasts with *steady-state* information, in which either the same auditory event is repeated (e.g. A-A-A-A-A) or the event is continuous, containing no or only gradual perceptual changes, for example white noise (Jones, Miles, & Page, 1990) or pitch glides (Jones et al., 1992).

Speech is particularly disruptive as it contains many abrupt changes across numerous dimensions from one utterance to the next. Whether the effects of irrelevant speech are qualitatively different to the effects of irrelevant non-speech sound is disputed (Jones & Macken, 1993; LeCompte, Neely, & Wilson, 1997; Neath, 2000; Neath, Surprenant, & LeCompte, 1998; Salamé & Baddeley, 1982; Tremblay, Nicholls, Alford, & Jones, 2000), but there is little doubt that, to a large extent, the effects of both irrelevant speech and non-speech sound are dictated by their acoustic characteristics. This has led Jones and colleagues (Jones, 1992; Jones, Beaman, & Macken, 1996; Jones & Macken, 1993) to suggest a 'changing-state hypothesis' which states that cues to the relative order of the auditory events are coded by changes within the irrelevant sound, and these conflict with similar cues to serial order which are required to successfully carry out a number of immediate memory tasks (e.g. Beaman & Jones, 1997).

The notion of changing-state is crucial to the ISE and 'may be regarded as the empirical signature of the irrelevant sound effect' (Jones, Macken, & Nicholls, 2004, p. 658). Anything that acts to reduce the number and extent of 'changes in state' must, perforce, also reduce the size of the auditory distraction effect. It follows from the changing-state hypothesis that heavily reverberant environments, small spaces with hard, non-absorbent surfaces may in fact produce a smaller distraction effect than larger spaces with softer, absorbent surfaces. This predicts that highly reverberant environments will be less intrinsically distracting environments in which to work than environments with shorter reverberation times, contrary to the suppositions of manufacturers of ceiling tiles and other acoustic treatments.

In a reverberant environment the direct signal is overlayed with multiple reflections, the intensity of each reflection and the delay imposed upon it being a function of the intensity of the original signal and the nature (e.g. the size, surfaces and contents) of the room. The addition of such reflections results in a smoothing of the profile of the waveform, with less significant peaks and troughs in the envelope of the sound, removing or attenuating both the number and degree of changes in state. It follows that larger spaces with more reverberation may intrinsically be less distracting environments (in acoustic terms) than small rooms with low levels of reverberation. This prediction follows from the changing-state hypothesis of Jones and colleagues. However, as currently formulated, the hypothesis says nothing about the amount of reverberation required to reduce the auditory distraction effect, and whether the distraction reduction will be apparent in everyday or only in extreme environments.

Perham and Jones (in press) have suggested that 'realistic' reverberation levels do not reduce auditory distraction and in a recent study have failed to find any significant differences in auditory distraction when reverberation times are held at either 0.7 or 0.9 second, with both levels providing the same distraction effect relative to quiet. However, their experiment is problematic in two ways. First, they are reliant upon a null prediction but their calculation of the statistical power of their experiment is misleading. Second, Perham and Jones do not show any effect of manipulating reverberation levels as would be predicted by the changing-state hypothesis and it is, therefore, unclear whether their acceptance of the null equates to a rejection of this hypothesis or whether their manipulation is not considered sufficient to test the hypothesis. By extension, if the manipulation is not a true test of the changing-state hypothesis it may not be a true test of reverberation effects either.

Perham and Jones (in press) report the statistical power associated with finding an effect between all three levels of their repeated measures variable (0.9 second reverberation time

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noise, 0.7 second reverberation time noise and quiet control), not simply between two different levels of reverberation. Tests for a small difference between the two reverberation conditions (power = 0.8) require 100 participants if Perham and Jones' assumption that the correlation between the two conditions (rho = 0.75) is correct, or more if rho < 0.75 (e.g. 180 if rho = 0.5). These participant numbers are impractical for most purposes, therefore we propose to take a different approach and ask whether extreme values of reverberation, which we expect to represent a powerful manipulation, will affect the results obtained for a much smaller sample size. The advantage of this approach is that it makes positive, rather than null, predictions and provides a direct test of the changing-state hypothesis. We will return to the complex issue of how to interpret small effect sizes in applied research in the discussion.

EXPERIMENT 1

The first experiment examines whether less reverberant environments are intrinsically less distracting, or whether the contrary view that an *increase* in reverberation might reduce distraction is correct. The former prediction represents the untested working hypothesis of those manufacturers in the noise reduction industry involved in the design and construction of acoustic ceilings and noise cancellation headphones (Perham & Jones, in press). The latter view can be attributed to the idea derived from Jones' (1992) changing-state hypothesis, that smoothing the acoustic signal by adding an extra, interfering acoustic wave in the form of reverberation or echo will reduce the amount of changing-state information in the acoustic stream and hence also the size of the irrelevant sound distraction effect (Jones & Macken, 1995; Jones, Alford, Macken, Banbury, & Tremblay, 2000) even if the speech remains perfectly intelligible.

The possibility that reverberation might actively reduce the ISE in real-world environments was first discussed by Beaman (2005a). The changing-state hypothesis admits the possibility but does not predict the type of auditory environment (i.e. the amount of reverberation) required to reduce the effect, whereas other extant theories of auditory distraction are, at best, mute concerning the possibility of an environmentally mediated distraction effect. Perham and Jones' (in press) data, in failing to find a difference between reverberation levels, do not adequately address the changing-state hypothesis: the null effects observed by Perham and Jones may be viewed as a refutation of the predictions of the changing-state hypothesis or may simply reflect inadequate power to detect the small effects of a weak manipulation.

Currently, the main competitor to the changing-state hypothesis is the attentional capture hypothesis of Cowan (1995), which also forms a part of Neath's (2000) application of the feature model of immediate memory (Nairne, 1990) to ISEs. This attentional capture hypothesis suggests that orientation to each irrelevant speech utterance (or other auditory distracter) depletes the pool of attentional resource available for the primary, immediate memory task. Reverberation need have no necessary consequences for an account of this type as there is no reason to suppose that orientation to the direct signal would be affected by the addition of an indirect signal (the echo). Thus, testing for an effect of extreme reverberation in the environment acts as the direct test of the changing-state hypothesis absent from Perham and Jones (in press). Further, any such effect would tend to support the changing-state hypothesis over its competitors.

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Method

Participants

Eleven students of Bath Spa University volunteered to participate in this study. All participants reported normal hearing levels and normal or corrected-to-normal vision. All had English as their first language.

Materials and design

Sounds were digitally recorded on Minidisk and presented from a Sony minidisk player at a comfortable listening level to students through Sennheiser HD570 headphones. Listening levels were set to a comfortable level with a test recording before the experiment began and kept at the same level for the duration of the experiment. Stimuli were presented on a Pentium Class PC running Windows XP and MS Powerpoint software.

The speech used in the irrelevant stream was digitally sampled from BBC Radio 4's 'Women's Hour'. Three levels of reverberation were applied to the sound using Cool Edit sound editing suit (Syntrillium Software Corporation). The full 24-minute sound recording was high pass filtered at 50 Hz. Two seconds amplitude ramps were added to the ends of the recording to remove any sharp onset and offsets. The total length of each reverberation was set at 5000 milliseconds, with an attack time of 200 milliseconds. These values give a 5 seconds reverberation tail, reaching a maximum level at 200 milliseconds. The amount of the original signal in the reflections was set at 60%. The proportion of the original signal in the sound gives a feeling of distance. The higher the original sound level, the nearer the perceived distance to the sound source, the 60% level gave a compelling feeling of depth to the reflections. The percentage of early reflections in the signal was set at 72%. Early reflections give a feeling of ambience to the sound. Since simulated room size was to be used to manipulate the reverberation level and give the independent variable, early reflections were set relatively high, providing a prominence to the early arriving sounds, those which give information about the room function. Pilot listening indicated that at these levels the variables gave a natural sounding and undistorted reverberation. Two experimental conditions were achieved by manipulating room size. Sounds produced using room simulations of 20 000 and 60 000 m^3 were noticeably different and were chosen as conditions 2 (low reverb) and 3 (high reverb), respectively. These room sizes are approximately comparable to those of a large lecture hall or opera theatre.

The effect of the reverberation with these parameters can be seen in Figure 1. Panel 1 shows the dry, unmanipulated recording of the words 'The Irrelevant Sound Effect'. Panels 2 and 3 show how, by comparison, the profile of the sound is smoothed by the two reverberation levels detailed above. The overall length of the recording is also altered as a function of the multiple reflections being added back to the original sound.

The visual stimuli consisted of lists of seven digits sampled quasi-randomly and without replacement from the range 1–9, each digit presented in succession in each trial. The font used was Arial of size 44. Each digit was presented for 0.5 second, followed by interstimulus intervals also of 0.5 second. Digit lists were constructed so as to be without upward or downward runs of longer than two successive items.

Four conditions were presented, each with 15 trials, giving a total number of 60 experimental trials per participant. Presentation order for each candidate was chosen randomly from the 24 possible condition orders. The four conditions were the three levels of reverberation in the irrelevant stream as described above and a 'no sound' control condition.

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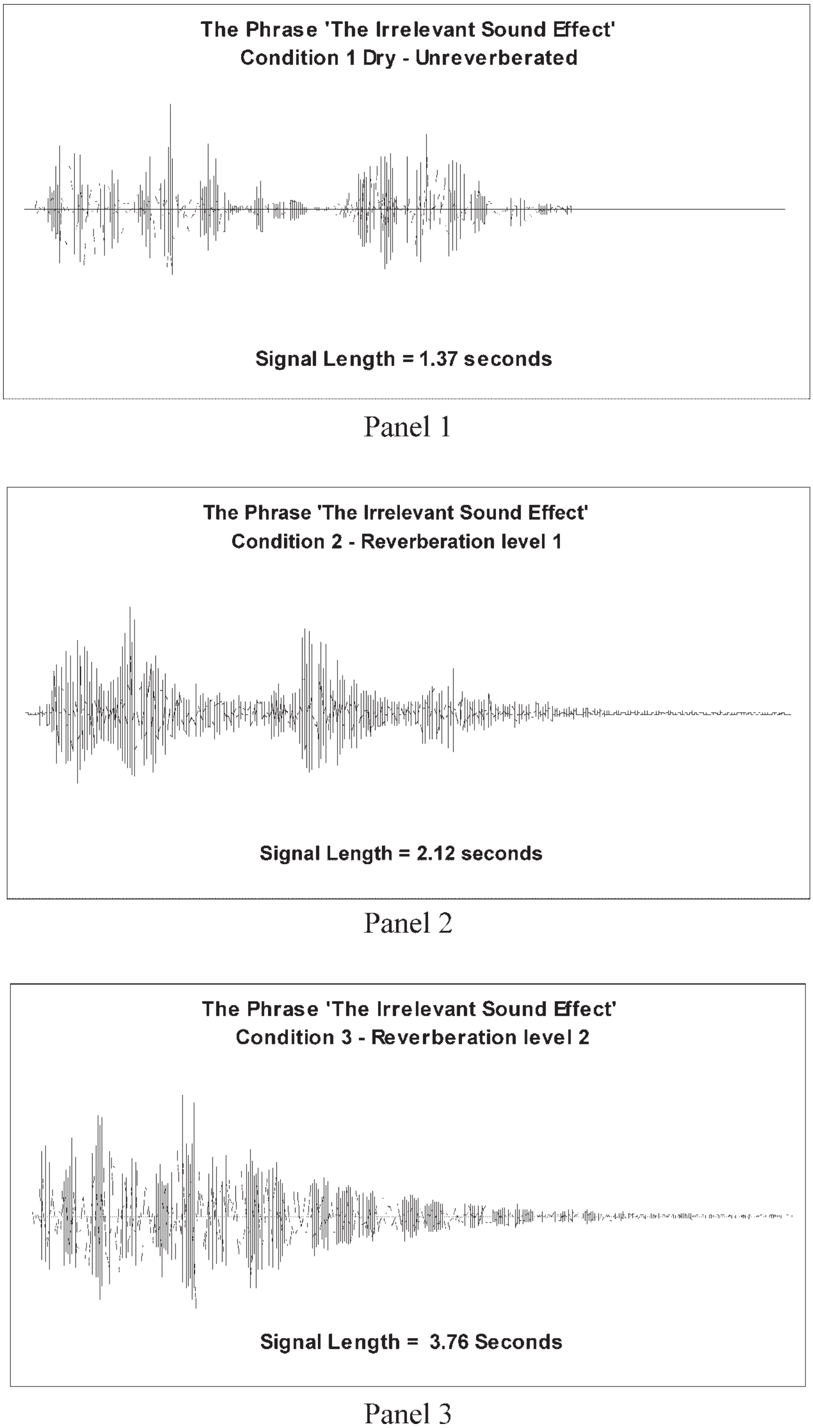

Figure 1. The effects of reverberation upon a segment of speech. Panel 1 shows the unreverberated ('dry') appearance of the speech and Panels 2 and 3 demonstrate how the addition of reverberation smoothes the profile of the sound

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Procedure

Each participant was tested individually in a quiet room. The irrelevant sound was presented continuously during each condition block, throughout the presentation, recall and inter stimulus intervals, directly from the digital recording. Participants were instructed to ignore anything they might hear and were reassured they would not be tested on it in any way. In each trial within each condition, the seven numbers were presented in succession on a VDU. After the presentation the instruction 'recall now' was presented. Participants recorded the numbers manually on response sheets provided, writing from left to right. They were asked not to omit any responses and, if they could not remember a particular item, to write down their best guess and move onto the next item. They were asked not to go back and amend previous answers if they felt they had made an error. The visual instruction 'Push space for next trial' cued participants to progress through the experiment.

Results

To be scored as correct, an item had to be recalled in the correct serial position. Two-way repeated measures analysis of variance (ANOVA) using four levels of auditory condition and seven levels of serial position showed a significant effect of irrelevant speech condition on the mean number correctly recalled, $F(3, 30) = 4.24$, $MSE = 16.21$, $p = 0.013$, a significant effect of serial position, $F(6, 60) = 2.58$, $MSE = 17.32$, $p = 0.027$, but no significant interaction between these two factors, $F(18, 180) = 1.13$, $MSE = 3.58$, $p = 0.326$. Figure 2 shows the effect of the manipulation on recall levels at each serial position.

Bonferroni corrected paired sample t-tests were carried out to determine which conditions differed significantly. Two pairwise comparisons were considered, quiet control versus no reverberation, and no reverberation versus high-level reverberation. Both contrasts remained significant following Bonferroni correction, the quiet control condition

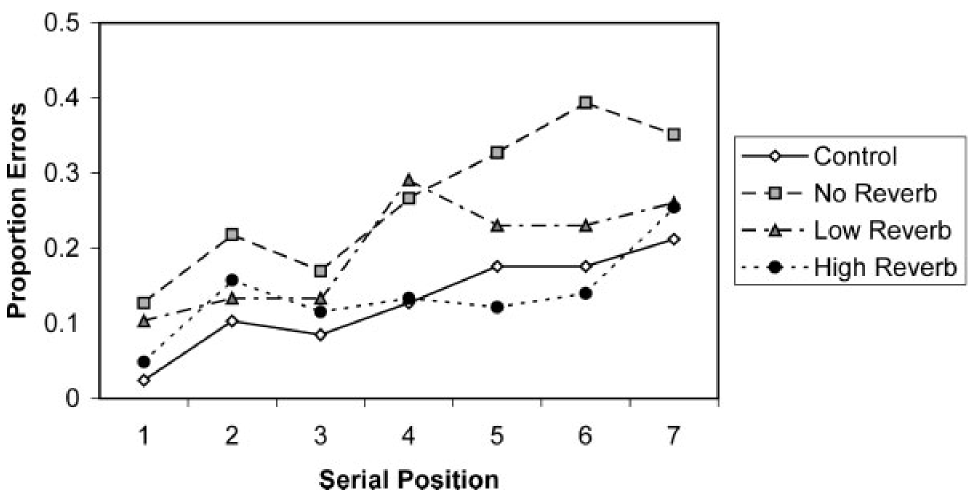

Figure 2. Experiment 1: Serial position curve showing the effects of reverberated irrelevant speech upon performance at an immediate memory task

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was significantly different from the no-reverberation condition, $t(10) = 4.32$, $p < 0.01$ and the no-reverberation differed significantly from the high reverberation, $t(10) = -3.67$, $p < 0.01$ (p values refer to observed significance levels following Bonferroni correction). No other conditions differed significantly ($p > 0.1$ before Bonferroni correction in all cases).

Discussion

Experiment 1 serves to test the general principle that adding reverberation to an unwanted and, arguably, unattended speech stream reduces the size of the ISE. This experiment provides support for the idea that an echo-intensive environment reduces rather than increases the size of the ISE, and hence the experiment also provides further support for the more general claims of Jones and colleagues and their changing-state hypothesis. However, in this experiment, the irrelevant sound was played continuously throughout each trial and the addition of reverberation to the sound stimuli in the medium and high reverberation conditions extended the length of the signal in each condition. For example, Figure 1 shows that a 1.37-second segment of conversation, when reverberated resulted in an acoustic signal considerably longer (the total increase being dependent upon the exact amount of reverberation added). This means that, since presentation of the speech was on a continuous repeat loop, the length of time exposed to the speech was equivalent in each condition, but the number of words presented per condition may have varied quite considerably. In the unreverberated condition, the number of words presented is greater than in the high reverberation condition across identical time periods and speech exposures. Previous research has indicated that the number of utterances, rather than the length of the signal, governs the size of the ISE, with a greater effect being observed when more utterances are heard, regardless of the total speech exposure time (Bridges & Jones, 1996). Thus, although consistent with the idea that reverberation reduces the ISE, it is possible to interpret the data from the current experiment as simply an effect of ‘word-dose’ (Bridges & Jones, 1996). Accordingly, a second experiment was carried out with a larger sample size and controlling for word-dose in addition to total signal exposure.

EXPERIMENT 2

Method

Participants
Twenty-four students of Bath Spa University volunteered to participate in this study. All participants reported normal hearing levels and normal or corrected-to-normal vision. All had English as their first language. None had participated in the previous experiment.

Materials and design
To control for word-dose a sample of the original ‘dry’, unreverberated recording was taken. The sample was reverberated as detailed previously to provide two reverberation conditions and a dry condition. As shown in Figure 1, the overall length of the signal is lengthened by reverberation. Presentation of the sample concurrent with presentation of the to-be-remembered items provides the listener with fewer repetitions of the sample and, therefore, a lower word-dose as reverberation level increases. To control for this, the

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samples in the dry no reverberation condition and the lower reverberation condition were padded with noise so that the overall duration of the presentation of irrelevant sound in each condition was equivalent. Participants heard the same number of utterances in each condition but at different rates of presentation, with fewer utterances per unit of time in the high reverberation condition. To equate the number of utterances, the conversation was played an equivalent number of times in each auditory condition, with brown noise added to make up the remaining time in the low- and no-reverberation conditions. The concern here was to pad the sound to compensate for increased length as a function of the reverberation manipulation while controlling for word-dose. It might be argued that adding sound to the irrelevant stream increases the complexity and richness of the signal in terms of 'changing-state' information. The sound was chosen carefully to limit this possibility. Brown noise qualifies as 'steady-state' under Jones' definition (e.g. Jones et al., 1992) and the presence of brown noise in these sections is, therefore, not expected to influence the ISE. Brown noise is white noise integrated with respect to time, giving stimuli with amplitude inversely proportional to frequency. It was used as padding because the low-frequency makeup of the noise was rated as less unpleasant in pilot testing than white noise, where the high frequencies appear much louder.

The design was as detailed for Experiment 1, with some minor changes. The onset of the irrelevant sound in each condition was cued to begin with the to-be-remembered items, and timed to last for the presentation duration of the to be remembered items. Sound was presented digitally through the headphones via a creative extigy digital sound card connected to the PC. Each participant received 25 trials in each condition. Order was fully counterbalanced. The condition order for each participant was chosen from the set of 24 possible orders without replacement.

Procedure

The procedure was identical to that of the first experiment.

Results

One-way repeated measures ANOVA once again revealed a significant within-participants effects of speech condition on the mean number correctly recalled, $F(3, 69) = 15.77$, $MSE = 0.38$, $p < 0.001$. Analysis of serial position is not included here as it did not emerge as a significant factor previously and there are no theoretical or practical considerations dependent upon the presence or absence of an auditory condition by serial position interaction. Figure 3 shows the effect of the speech condition manipulation on recall levels averaged across serial position.

The same pairwise comparisons were considered as previously. Following Bonferroni correction, the quiet control condition was significantly different from the no-reverberation condition, $t(23) = 5.21$, $p < 0.01$, the quiet control condition also differed significantly from the low-reverb condition, $t(23) = 6.07$, $p < 0.01$ and the high-reverberation condition was significantly different from the no reverberation condition, $t(23) = -4.44$, $p < 0.01$. No other contrasts differed significantly, even prior to Bonferroni correction ($p > 0.1$ in all cases).

Discussion

The results of Experiment 2 replicate the general pattern observed in Experiment 1 and confirm that, when word-dose is controlled, there is a significant reduction in the ISE when

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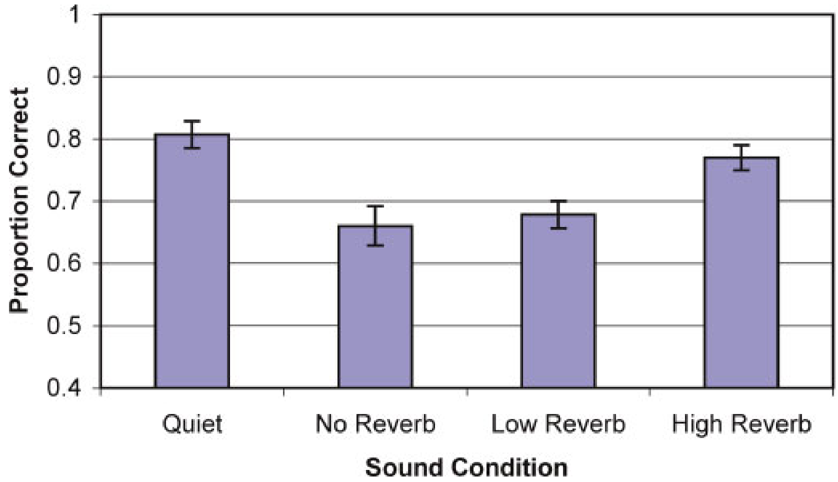

Figure 3. Experiment 2: The effects of reverberated irrelevant speech upon performance at an immediate memory task controlling for word-dose within the irrelevant speech stream and averaged over serial position

the acoustic signal is heavily reverberated. Additionally, there is nothing in the results to indicate that the addition of brown noise to the irrelevant stream (outlined in the Materials and design section) made the stream as a whole any richer in terms of changing-state information. Overall, the results do not support the general claim that attempting to absorb noise and reduce echo in workplace environments reduces the likelihood of observing auditory distraction effects. Rather, a decrease in the size of the ISE may be observed if there is sufficient reverberation of the irrelevant auditory signal, simulated here as a virtual auditory environment to allow thorough experimental investigation.

GENERAL DISCUSSION

The results of these experiments are supportive of the view that the extent of auditory distraction observed is dictated by the number of 'changes in state' that occur within the irrelevant sound stream and that anything which acts to reduce the number or extent of these changes will reduce the size of the distraction effect (see Jones et al., 1999 for systematic exceptions to this rule). As such, the results are consistent with the changing-state hypothesis and add to the weight of theoretical evidence in support of this hypothesis. One important effect of adding reverberation is to blunt the boundaries between successive utterances, possibly reducing the segmentation experienced within the irrelevant speech, a manipulation that might be expected to reduce the irrelevant sound disruption effect according to the changing-state hypothesis (Jones, Macken, & Murray, 1993). The words in the irrelevant stream in these experiments were not, so far as can be ascertained by passive listening, rendered unintelligible by the process of adding reverberation, although no formal tests were carried out on whether the relative levels of intelligibility varied between the conditions and that remains a limitation of the current study. However, unintelligible speech (e.g. reversed speech or speech in a foreign language) produces distraction effects comparable to that of intelligible speech (Jones, 1992) so this limitation may be more apparent than real.

The present results are inconsistent with the view that it is always helpful, when aiming to optimise cognitive efficiency, to reduce the level of reverberation within the environment. Extensive echo produces similar effects to background 'babble' in reducing or eliminating the ISE for visually-presented tasks (Jones & Macken, 1995). This effect is independent of the word-dose (Bridges & Jones, 1996) or number of utterances within the irrelevant speech stream (Experiment 2). These experiments are the first to demonstrate that intrinsic factors of particular environments can modify the extent of auditory distraction objectively observed in such environments. However, these conclusions must be restricted to the *objective* measurements of auditory distraction here as there are frequent anecdotal suggestions that certain individuals work better, or at any rate are undisturbed, by the presence of background music or noise. To date, only weak associations have been found between the reported subjective experience and the observed objective measurements of auditory distraction (Beaman, 2005b; Ellermeier & Zimmer, 1997) despite the demonstrable individual differences in distractibility (Ellermeier & Zimmer, 1997). Perham and Jones (in press) also report that low levels of reverberation were preferred in their experiment even though, in their data, no objective differences in performance were found between the two sound conditions. It may be that the psychophysical aspects of the environment addressed here, which affect objective measurements of distractibility, dissociate from other environmental (e.g. aesthetic) considerations, which may influence the subjective feelings of those tested without necessarily impacting upon the objective results obtained. These objective environment-mediated reductions in the auditory distraction effect occur only with relatively high levels of reverberation, however, as demonstrated here.

Small effect sizes and applied research

If only unrealistically or extremely echoic environments reduce the ISE, are there any human factors or ergonomic conclusions to be drawn from the current research beyond the theoretical test confirming the predictions of the changing-state hypothesis? Perham and Jones (in press) found no effect of reverberation when the reverberation times under comparison were in line with those observed in acoustically-treated or untreated offices. As stated earlier, however, Perham and Jones' data suggest that there is no effect of moderate levels of reverberation only under the assumption that moderate levels of reverberation would produce a medium to large effect size, and this is consistent with the findings reported here. A small effect of moderate reverberation, however, may pass unnoticed in Perham and Jones' data because of the lack of power to detect such an effect. If the effect of adding reverberation to irrelevant sound is linear, as is the effect of degrading the irrelevant sound by low-pass filtering (Jones et al., 2000), then one might expect a progressively smaller reverberation effect as reverberation times decrease.

Small effect sizes that may be of little or no theoretical import cannot be easily dismissed because they may have important practical consequences. An effect size that is invisible within a laboratory setting with a limited pool of participants may scale up to show a large impact on a general population of thousands of individuals in distracting environments, particularly where many of these individuals are working in safety-critical environments with little margin for error (see Beaman, 2005a; Hughes & Jones, 2001, 2003 for reviews). A small effect at the individual or small-group level may be far more consequential at the

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societal level when large sections of the population are involved and applied research into memory and cognition should take notice of such considerations. In the present case, however, some irrelevant sound manipulations other than low-pass filtering are known to produce non-linear effects on working memory tasks, for example adding progressively more ‘change’ to a changing-state auditory stream ultimately reduces the level of disruption observed (Jones et al., 1999). The simple fact of observing an effect of reverberation on auditory distraction at high reverberation levels suggests but does not conclusively show that a smaller effect will necessarily be observed with smaller and more everyday levels of reverberation.

In conclusion, we have established that reverberation can reduce the auditory distraction effect produced by irrelevant speech. Highly reverberant auditory environments are, intrinsically, less distracting by virtue of the transfer function in existence within such environments. Informal observations also suggest that even the highly reverberated speech is intelligible upon first presentation which, if confirmed by further study, sets this manipulation apart from other signal-processing techniques that reduce the intelligibility of the irrelevant speech (e.g. Jones et al., 2000). Various other possibilities include whether reverberated speech might also mediate the semantic effects of meaningful auditory distracters (Neely & LeCompte, 1999) and which parts of the speech signal (e.g. onset, offset, etc.) smoothed by reverberation carry the disruptive changing-state information (Hughes, Tremblay, & Jones, 2005). Research along these lines, in conjunction with the data already reported, should add to our understanding of cognitive performance in noise. Further research looking at the subjective experience of such noise should, in addition, lead to a greater understanding of how auditory environments can be made more conducive to efficient cognitive function both objectively and subjectively.

REFERENCES

Banbury, S. P., & Berry, D. C. (1997). Habituation and dishabituation to speech and office noise. *Journal of Experimental Psychology: Applied*, *3*, 181–195.

Banbury, S. P., & Berry, D. C. (1998). The disruption of office-related tasks by speech and office noise. *British Journal of Psychology*, *89*, 499–517.

Banbury, S. P., Tremblay, S., Macken, W. J., & Jones, D. M. (2001). Auditory distraction and short-term memory: Phenomena and practical implications. *Human Factors*, *43*, 12–29.

Barceló, J. A., Forte, M., & Sanders, D. H. (2000). *Virtual reality in archaeology.* Oxford: Archaeopress.

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.

Beaman, C. P. (2005a). Auditory distraction from low-intensity noise: A review of the consequences for learning and workplace environments. *Applied Cognitive Psychology*, *19*, 1041–1064.

Beaman, C. P. (2005b). Irrelevant sound effects amongst younger and older adults: Objective findings and subjective insights. *European Journal of Cognitive Psychology*, *17*, 241–266.

Beaman, C. P., & Jones, D. M. (1997). The role of serial order in the irrelevant speech effect: Tests of the changing-state hypothesis. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *23*, 459–471.

Beaman, C. P., & Jones, D. M. (1998). Irrelevant sound disrupts order information in free as in serial recall. *Quarterly Journal of Experimental Psychology*, *51A*, 615–636.

Bridges, A. M., & Jones, D. M. (1996). Word-dose in the disruption of serial recall by irrelevant speech. *Quarterly Journal of Experimental Psychology*, *49A*, 919–939.

Cowan, N. (1995). *Attention and memory: An integrated framework*. Oxford: Clarendon Press.

Ellermeier, W., & Zimmer, K. (1997). Individual differences in susceptibility to the ''irrelevant speech effect''. *Journal of the Acoustical Society of America*, *102*, 2191–2199.

Elliott, E. M., & Cowan, N. (2005). Coherence of the irrelevant sound effect: Individual profiles of short-term memory and susceptibility to task-irrelevant materials. *Memory & Cognition*, *33*, 664–675.

Hughes, R., & Jones, D. M. (2001). The intrusiveness of sound: Laboratory findings and their implications for noise abatement. *Noise & Health*, *4*, 51–70.

Hughes, R. W., & Jones, D. M. (2003). Indispensable benefits and unavoidable costs of unattended sound for cognitive functioning. *Noise& Health*, *6*, 3–76.

Hughes, R. W., Tremblay, S., & Jones, D. M. (2005). Disruption by speech of serial short-term memory: The role of changing-state vowels. *Psychonomic Bulletin & Review*, *12*, 886–890.

Jones, D. M. (1992). Objects, streams and threads of auditory attention. In A. D. Baddeley, & L. Weiskrantz (Eds.), *Attention: Selection, awareness and control*. Oxford: Clarendon Press.

Jones, D. M., Alford, D. K., Bridges, A., Tremblay, S., & Macken, W. J. (1999). Organizational factors in attention: The interplay of acoustic distinctiveness and auditory streaming in the irrelevant sound effect. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *25*, 464–473.

Jones, D. M., Alford, D., Macken, W. J., Banbury, S., & Tremblay, S. (2000). Interference from auditory degraded stimuli: Linear effects of stimulus mismatch in the irrelevant sequence. *Journal of the Acoustical Society of America*, *108*, 1082–1088.

Jones, D. M., Beaman, C. P., & Macken, W. J. (1996). The object-oriented episodic record model. In S. E. Gathercole (Ed.), *Models of short-term memory.* Hove: Psychology Press.

Jones, D. M., & Macken, W. J. (1993). Irrelevant tones produce an irrelevant speech effect: Implications for phonological coding in working memory. *Journal of Experimental Psychology: Learning, Memory & Cognition, 19*, 369–381.

Jones, D. M., & Macken, W. J. (1995). Auditory babble and cognitive efficiency: Role of number of voices and their location. *Journal of Experimental Psychology: Applied*, *1*, 216–226.

Jones, D. M., Macken, W. J., & Mosdell, N. (1997). The role of habituation in the disruption of recall performance by irrelevant sound. *British Journal of Psychology*, *88*, 549–564.

Jones, D. M., Macken, W. J., & Murray, A. (1993). Disruption of visual short-term memory by changing-state auditory stimuli: The role of segmentation. *Memory & Cognition*, *21*, 318–328.

Jones, D. M., Macken, W. J., & Nicholls, A. P. (2004). The phonological store of working memory: Is it phonological and is it a store? *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *30*, 656–674.

Jones, D. M., Madden, C. A., & Miles, C. (1992). Privileged access by irrelevant speech to short-term memory: The role of changing-state. *Quarterly Journal of Experimental Psychology*, *44A*, 645–669.

Jones, D. M., Miles, C., & Page, J. (1990). Disruption of proof-reading by irrelevant speech: Effects of attention, arousal or memory? *Applied Cognitive Psychology, 4*, 89–108.

Larsen, J. D., & Baddeley, A. D. (2003). Disruption of verbal stm by irrelevant speech, articulatory suppression and manual tapping: Do they have a common source? *Quarterly Journal of Experimental Psychology*, *56A*, 1249–1268.

LeCompte, D. C. (1994). Extending the irrelevant speech effect beyond serial recall. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *20*, 1396–1408.

LeCompte, D. C., Neely, C. B., & Wilson, J. R. (1997). Irrelevant speech and irrelevant tones: The relative importance of speech to the irrelevant speech effect. *Journal of Experimental Psychology: Learning, Memory & Cognition, 23*, 472–483.

Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition, 18*, 251–269.

Neath, I. (2000). Modeling the effects of irrelevant speech on memory. *Psychonomic Bulletin & Review*, *7*, 403–423.

Neath, I., Surprenant, A. M., & LeCompte, D. C. (1998). Irrelevant speech, phonological similarity and presentation modality. *Memory, 7*, 405–420.

Neely, C. B., & LeCompte, D. C. (1999). The importance of semantic similarity to the irrelevant speech effect. *Memory & Cognition*, *27*, 37–44.

Perham, N., & Jones, D. M. (in press). Realistic reverberation levels do not reduce auditory disruption. *Applied Cognitive Psychology.* DOI: 10.1002/acp.1300

Ruddle, R. A., Payne, S. J., & Jones, D. M. (1998). Navigating large-scale 'desk-top' virtual buildings: Effects of orientation aids and familiarity. *Presence: Teleoperators & Virtual Environments*, *7*, 179–192.

Ruddle, R. A., Payne, S. J., & Jones, D. M. (1999). Spatial knowledge and virtual environments. In J. M. Noyes, & M. Cook (Eds.), *Interface technology: The leading edge* (pp. 135–146). Baldock, England: Research Studies.

Salamé, P., & Baddeley, A. D. (1982). Disruption of short-term memory by unattended speech: Implications for the structure of working memory. *Journal of Verbal Learning & Verbal Behavior*, *21*, 150–164.

Tremblay, S., & Jones, D. M. (1998). The role of habituation in the irrelevant sound effect: Evidence from the effects of token set size and rate of transition. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *24*, 659–671.

Tremblay, S., Nicholls, A. P., Alford, D., & Jones, D. M. (2000). The irrelevant sound effect: Does speech play a special role? *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *26*, 1750–1754.

Wann, J. P., & Rushton, S. K. (1995). The use of virtual environments in perception-action research: Grasping the impossible and controlling the improbable. In D. Glencross, & J. Piek (Eds.), *Motor control and sensory-motor integration*. Amsterdam: North-Holland.

Wann, J. P., Rushton, S. K., Smyth, M., & Jones, D. (1997). Rehabilitation environments for attention and movement disorders. *Communications of ACM*, *40*, 49–52.

Watson, A. (2001). The sounds of transformation: Acoustics, monuments and ritual in the British Neolithic. In N. Price (Ed.), *The archaeology of Shamanism* (pp. 178–192). London: Routledge.

Watson, A., & Keating, D. (1999). Architecture and sound: An acoustic analysis of megalithic monuments in prehistoric Britain. *Antiquity*, *73*, 325–36.

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