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Auditory Attentional Capture: Effects of Singleton Distractor Sounds

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Abstract

The phenomenon of attentional capture by a unique yet irrelevant “singleton” distractor has typically been studied in visual search. Here we examine whether a similar phenomenon occurs in the auditory domain. Participants searched sequences of sounds for targets defined by frequency, intensity or duration. The presence of a “singleton” distractor that was unique on an irrelevant dimension (e.g. a low frequency singleton in search for a target of high intensity) was associated with search costs in both detection and discrimination tasks. However if the singleton feature coincided with the target item, search was facilitated. These results establish the phenomenon of auditory attentional capture.

Auditory Attentional Capture: Effects of Singleton Distractor Sounds

The brain receives an overwhelming amount of information from all the senses at the same time. In order to respond to this stimulation appropriately, relevant stimuli must be selected for further processing while other, less relevant stimuli must be ignored. Many studies have shown that people are able to focus attention efficiently on a subset of goal-relevant stimuli as long as the relevant and irrelevant stimuli differ from each other on the basis of a simple visual feature. For example, participants can be very efficient at searching for targets defined by curved features among nontargets with angular features (for review see Treisman, 1988; Duncan & Humphreys, 1989). Although most of the nontargets in such search tasks can be ignored, recent research suggests that if one of them is presented with a unique feature that makes it a singleton in the visual field (e.g. if it is red while the other nontargets are green) it will typically interfere with search (e.g. Theeuwes, 1992). This interference occurs even though the distractor object is a singleton on a dimension that is never relevant to the task, suggesting that attention is captured by the singleton distractor rather than being voluntarily allocated to it. It seems likely that attention is tuned towards unique perceptual objects (such as singletons) because such objects are different from the background and thus may indicate an important change in the environment.

The phenomenon of attentional capture (AC) by an irrelevant singleton distractor has been studied extensively in visual search (for review see Yantis, 2000).[1] The purpose of the present study was to examine whether a similar phenomenon can be found in the auditory domain. Because hearing is free from the spatial restrictions of the other senses, one of its functions may be to act as an “early warning” system (e.g. Scharf, 1998) that allows us to monitor for changes in the environment. We might therefore expect that auditory attention would be tuned to unique distractor sounds (e.g. sounds with a singleton feature) and would thus be open to capture by such sounds even when they are task-irrelevant.

Previous Studies of Auditory Selective Attention

Previous research has established that auditory attention, like visual attention, can focus on sounds containing a particular auditory feature. For example, early studies using the dichotic listening technique found that participants could selectively attend to a channel defined by a certain auditory feature (e.g. words spoken by a female voice) while apparently ignoring the channel that did not share that feature (e.g. words spoken by a male voice; e.g. Cherry, 1953; Moray, 1959). However these studies typically used complex semantic material (e.g. words or sentences) and the interpretation of their results was often complicated by having to consider the effects of semantic priming on the extent to which irrelevant stimuli were ignored. For example, irrelevant but pertinent words such as the participant's own name were often recognized even in the unattended channel (for review see Treisman, 1969).

Clearer effects of focused attention on auditory perception have been demonstrated in studies using simpler auditory stimuli (e.g. pure tones) that assess performance on the basis of detection or discrimination reaction times (RTs) and accuracy. These studies have demonstrated, for example, that auditory detection or discrimination is facilitated when sounds are presented at expected rather than unexpected frequencies or intensities (e.g. Greenberg & Larkin, 1968; Luce & Green, 1978; Mori & Ward, 1991, 1992, Nosofsky, 1983; Schröger and Wolff, 1998; Tanner &

Norman, 1954; Yama & Robinson, 1982). These findings suggest that attention can selectively focus on ranges of frequencies or intensities, facilitating responses to stimuli that fall within the attended range.

Studies of auditory cueing support this interpretation. For example, Mondor and Bregman (1994) asked participants to judge the durations of target tones. Responses were faster and more accurate when an auditory cue preceding the target was at the same frequency as the target (75% of trials), than when the two were at different frequencies (25%; see also Scharf, Quigley, Aoki, Peachey & Reeves, 1987). Similar studies have shown that auditory attention can also be drawn to previously cued intensities and durations (e.g. Mondor & Lacey, 2001).

Interestingly, as in visual attention (for review see Duncan & Humphreys, 1989), two main determinants of the efficiency of focusing auditory attention are the similarity between the relevant and irrelevant sounds (e.g. Leek, Brown & Dorman, 1991) and the similarity of the irrelevant sounds to each other (e.g. Alain & Woods, 1993; Bregman & Rudnicky, 1975). Both factors are important in setting up a target template that is clearly distinct from the nontarget template (e.g. Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Wolfe, 1994).

Finally, the suggestion that focused auditory attention can affect early perceptual processing of ignored sounds has received much support from event-related potential (ERP) studies. A typical finding is that ERPs elicited by attended sounds differ from ERPs elicited by the same sounds when they are ignored (for review see Hansen & Woldorff, 1991). These differences have been observed as early as 60 to 80 ms after stimulus presentation (e.g. Hansen & Hillyard, 1980) suggesting that focused attention can have an effect on the early perceptual processing of sounds.

To sum up, the studies reviewed so far demonstrate that attention can selectively focus on a subset of task-relevant auditory stimuli, and that such focusing of attention modulates auditory perception. The issue of AC by irrelevant singleton distractors concerns the extent to which such focused auditory attention is disrupted by the presence of an irrelevant singleton distractor. Although this issue has not yet been directly tested, some studies have addressed the general issue of distractor interference in the auditory domain, as we review below.

Distractor Interference Effects on Auditory Selective Attention

A few recent studies have examined the behavioural effects of auditory distractors. Mondor, Zatorre & Terrio (1998) found that participants responding to the frequency of successive tones performed better if those tones did not also vary on the irrelevant dimension of location (and the same effect was found for irrelevant variations in frequency when participants responded to location). Similarly Schröger and Wolff (1998) demonstrated that performance on a duration judgement task was worse if the sound being judged was of a low-probability "deviant" frequency, than if it was of a standard frequency. These results suggest that variation in an irrelevant dimension cannot always be successfully ignored.

However, in both of these studies the irrelevant variation was presented within the target sounds themselves. The study of visual attention has clearly established that people cannot attend selectively to one dimension of an object while ignoring another dimension of the same object (e.g. Duncan, 1984). Similarly, the findings of Mondor et al. (1998)

and Schröger and Wolff (1998) suggest that auditory attention cannot be selectively focused on one dimension of a sound while ignoring another dimension of the same sound. Visual AC has been found due to singleton distractors that are presented in a clearly separate nontarget object. The auditory studies discussed above cannot inform about participants' ability to ignore such nontarget sounds.

A more directly related study was carried out by Schröger (1996). He asked participants to make a go/no-go response according to the intensity of a sound presented to one ear, while ignoring a preceding sound presented to the other ear. The sound in the irrelevant ear could be either of standard frequency (88% of trials) or of deviant frequency (12% of trials). Both of these frequencies were irrelevant to the task as they were different from the frequency of the target sound. However, participants performed worse on the go/no-go intensity task when the preceding irrelevant sound was of deviant frequency than when it was of standard frequency. An explanation in terms of AC by the irrelevant deviants would fit these results. However as the sounds in the irrelevant ear always preceded the target in the relevant ear, participants could have used the irrelevant sounds as temporal precues to the target, perhaps willfully paying attention towards them (the interference by the deviant sounds would then be well accounted for by expectancy effects, e.g. Mori & Ward, 1991). In other words it is not clear whether the deviant sounds were processed because they captured attention or because attention was voluntarily allocated to all the preceding sounds in the irrelevant ear because of their ability to cue the target. In order to establish that attention was unintentionally captured by irrelevant singleton sounds it is important to ensure that they are truly irrelevant to the task. Such attempts were made in the study of AC in the visual domain, as we describe below.

Characteristics of Attentional Capture in Visual Search Tasks

As we have mentioned previously, many studies have established that RT in visual search for feature targets is independent of set size – a finding that seems to indicate that the irrelevant nontargets were excluded from attention (for review see Treisman, 1988). However research into visual AC has shown that the presence of a distractor with a unique yet irrelevant singleton feature can in fact interrupt such search. For example, Pashler (1988) found that search for an odd shape was interrupted by the presence of color singletons in the array, but not by random variation in the colour of the array elements (see also Theeuwes, 1992). The salience of the singleton relative to the target seems to be a critical factor in determining whether or not a particular singleton captures attention. Although colour singletons interfere with search for an odd shape, search for an odd colour may not always be disrupted by shape singletons. However, when shape singletons are made more salient than colour singletons (by making shape differences more discriminable than colour differences), shape singletons capture attention whereas colour singletons do not (Theeuwes, 1992). Thus the relative salience of different auditory features may be an important factor in determining whether or not particular auditory singletons will capture attention.

Another important factor seems to be the nature of the target task. Interference from singleton distractors is more likely to be found when the target is also a feature singleton,[2] and this interference can be eliminated simply by adding another target to the array, so that the target is no longer a singleton (Bacon & Egeth, 1994). Bacon and Egeth also found that AC was prevented if the nontargets were made heterogeneous. It therefore seems likely that AC by an auditory singleton distractor will depend on the target being defined by a simple auditory feature and on the nontargets (other than the singleton) being homogeneous.

Another characteristic of visual AC is that it leads to facilitation if the irrelevant singleton feature coincides with the target. In all of the visual AC experiments discussed so far it was the distractor that contained the irrelevant singleton feature, and AC was therefore measured in terms of interference with target detection, suggesting that attention was always drawn away from target towards an irrelevant item (see also Theeuwes, Kramer, Hahn, Irwin & Zelinsky, 1999). However, Jonides and Yantis (1988) also examined the effects of presenting the irrelevant singleton feature within the target itself. They found that the irrelevant feature of abrupt-onset interfered with search if it coincided with a distractor but facilitated search if it coincided with the target. This finding strengthens the claim that singletons capture attention and hence facilitate search if attention is captured by the relevant search target.

The Present Study

The tasks used in the present study were designed in line with the findings of the auditory and visual research discussed above. We designed an auditory search task in which participants were asked to search for an auditory feature target (e.g. defined by frequency) among irrelevant nontargets (with a different frequency) and indicate whether it was present or absent (Experiments 1-2) or discriminate its feature value (e.g. high frequency or low frequency, Experiments 3-6). One of the nontargets could also be presented with an irrelevant singleton feature (e.g. higher intensity) and we compared target RTs in the presence versus absence of this singleton distractor. As we have discussed, auditory research has suggested that participants can focus their attention on ranges of frequencies, intensities and durations. Thus the participants in the present study should also be able to focus on the relevant target feature. The question of current interest was whether the presence of a nontarget with a unique singleton feature would disrupt such focused attention.

We presented participants with rapid serial auditory presentation (RSAP) search arrays rather than the spatial arrays used in the visual research. We adopted this design for three reasons: First, there is a growing body of evidence to suggest that the auditory system, unlike the visual system, processes spatial location with lower priority than other stimulus attributes (e.g. Kubovy, 1981). For example, while visual areas of the cortex are spatiotopically organized, auditory cortex is organized primarily according to frequency (e.g. Merzenich, Colwell & Andersen, 1982). In line with these observations, behavioural studies have suggested that, in demanding tasks, participants are better at identifying auditory targets defined by frequency than those defined by location (e.g. Woods, Alain, Diaz, Rhodes & Odawa, 2001). A second, related point is that, because the auditory system has worse spatial resolution than the visual system, it tends to integrate several inputs presented from different spatial positions at the same time into a single perceptual object. In search tasks such as those used in studies of visual AC it is very important that the items to be searched are identifiable as separate perceptual objects (as the aim is to demonstrate interference due to an irrelevant singleton feature that is presented in a distractor object, clearly separate from the target object). A temporal auditory array will allow clearer identification of separate objects than a spatial auditory array. Finally, most previous research into focused auditory attention and the effects of auditory distractors has used temporal rather than spatial search arrays.

Experiment 1A

In Experiment 1A, participants were asked to search a sequence of four sounds for a particular target sound, and indicate whether the target was present or absent. Targets were defined as being of higher frequency than the nontargets for half of the participants, and of lower frequency than the nontargets for the other half of the participants. The difference in frequency between nontargets and targets was 80 Hz. Given a baseline target frequency of 520 Hz (half the subjects) or 440 Hz (the other half of the subjects), a difference of 80 Hz is larger than the band of frequencies that auditory attention is thought to be able to focus upon (with these values the attentional band covers approximately 50 Hz, e.g. Scharf et al., 1987; Dai, Scharf & Buus, 1991). Thus participants should be able to focus attention on the target frequency while ignoring the nontarget frequency.

On half of the trials, one of the nontarget sounds was presented at a higher intensity than the other sounds and target RTs were measured as a function of the presence or absence of that singleton. If such an auditory distractor captures attention despite having an irrelevant frequency and being specified as a singleton on the irrelevant dimension of intensity, this should produce a cost to target reaction times (RTs) on singleton present trials compared with singleton absent trials.

Method

Participants. Eight participants took part in the experiment. The participants in all of our experiments were students at University College London and were paid £5 for participation. All the participants were under 35 years old and reported normal hearing.

Apparatus and stimuli. The experiments were created and run on a PC using E-Prime (1.0 beta 5.0 version), sold by Psychology Software Tools Inc. Auditory stimuli were created using the SoundEdit 16 software package, sold by Macromedia Inc. Auditory stimuli were presented through Beyer open-cup headphones.

High frequency targets (used for half of the participants) were presented with a frequency of 520 Hz among nontargets of 440 Hz. Low frequency targets (used for the other half of the participants) were presented with a frequency of 440 Hz among nontargets of 520 Hz. The targets and nontargets were presented at an intensity of approximately 72 dB SPL. The singleton sound was presented at approximately 83 dB SPL. Intensities were measured using a Brüel and Kjær artificial ear and sound pressure level meter at the participants' ear position. Frequencies and intensities were chosen to be easily discriminable, as verified by pilot testing.[3]

Procedure. The start of each trial was signalled by a screen, which displayed the word "ready" for 500 ms. This was followed by a stream of four successive sounds each presented for 100 ms over headphones. The sounds were separated from each other by 50 ms silent intervals. A question mark was presented on the screen at the end of the sound stream. Participants were requested to respond with a key press: "1" for "target present" or "2" for "target absent", using the index and middle fingers of the right hand respectively, upon presentation of this question mark. Visual feedback was provided at the end of each trial, either after a response had been collected or after 3000 ms if no response had been detected. The feedback screen displayed either the word “correct” presented in blue, “incorrect” presented in red or “no response detected” in red. This screen lasted 1500 ms, after which time the “ready” display was presented in preparation for the next trial. Participants were instructed to focus on the target frequency dimension and ignore any sounds of the irrelevant frequency. They were informed that there might be some odd sounds presented at the irrelevant frequency and were warned that their performance might be harmed if they failed to ignore the irrelevant distractors.

Six experimental blocks of 96 trials each were run. Within each block the factors of target presence and singleton presence were fully crossed so that there were four possible combinations of target and singleton presence, each occurring on 25% of the trials selected at random. The first sound in the sequence was always a nontarget. Targets and singleton distractors were presented at random in positions 2, 3 or 4 with equal likelihood. Three practice blocks of 24 trials each preceded the experimental blocks. In the first practice block, there was no time limit for responses and there was also a break between each trial to allow the experimenter to provide more detailed feedback if necessary. The second and third practice blocks followed exactly the same procedure as the experimental blocks.

Results and Discussion

Mean RTs and accuracy rates were calculated for each participant as a function of singleton presence (present vs. absent) and target presence (present vs. absent). For the RT analysis, incorrect responses were excluded from the analysis, as were RTs longer than 1500 ms. These exclusion criteria were used in all the experiments reported in this paper.

RTs. Table 1 presents mean RTs and error rates across participants as a function of singleton presence (vs. absence) and target presence (vs. absence). A two-way ANOVA with the within-subjects factors of singleton presence (vs. absence) and target presence (vs. absence) revealed a significant main effect of singleton presence ($F(1, 7) = 18.93$, MSE = 364.28, $p < .01$). As can be seen in Table 1, target RTs were slower in the presence vs. the absence of a singleton distractor, suggesting that the singleton distractor captured attention despite being irrelevant.[4] There was no effect of target presence ($F < 1$). However there was a significant interaction between singleton presence and target presence, ($F(1, 7) = 14.19$, MSE = 227.98, $p < .01$), reflecting a stronger effect of singleton presence on target absent trials than on target present trials (see Table 1), although the effect of singleton presence on target present trials was significant ($t(7) = 1.95$, $p < .05$). The finding that AC by the singleton distractor is not as strong when the target is present as well may be due to the need to compete with the target for attention when both are present.[5]

Errors. A similar ANOVA was run on the errors and replicated the main effect of singleton presence found in RTs ($F(1, 7) = 6.65$, MSE = .00034, $p < .05$). There was also a main effect of target presence on the errors, ($F(1, 7) = 6.44$, MSE = .00030, $p < .05$), suggesting that participants made more errors when the target was present than when it was absent, as shown in Table 1. In other words participants tended to have more misses than false alarms. There was no interaction between target presence and singleton presence in the errors ($F(1, 7) = 2.95$, MSE = .00013, $p = .13$).

--------------- Table 1 about here ---------------

Experiment 1B

The purpose of Experiment 1B was to examine whether the interference effects due to singletons of higher intensity than the other sounds can generalize to singletons of lower intensity than the other sounds. The singleton interference demonstrated in Experiment 1A may be attributed to a general startling effect caused by the singleton because it is louder than all the other sounds, rather than AC towards the singleton because it is unique.

Method

Participants. Eight new participants participated in this experiment.

Stimuli and Procedure. The stimuli and procedure were the same as in Experiment 1A except that the singleton distractor was presented with a lower intensity (approximately 72 dB SPL) than targets and nontargets (approximately 83 dB SPL). All other aspects of the method were the same as in Experiment 1A.

Results and Discussion

RTs. Table 1 presents mean RTs and error rates across participants as a function of singleton presence (vs. absence) and target presence (vs. absence). In line with the results of Experiment 1A, the RT ANOVA found a significant main effect of singleton presence ($F(1, 7) = 10.85$, $MSE = 696.42$, $p < .05$). Target RTs were slower when the singleton was present vs. absent (see Table 1), consistent with our predictions of AC by the irrelevant singleton. This is an important result, as the interference effect in the present experiment is due to singletons that were quieter than the other sounds, and as such cannot be explained in terms of a general startling effect due to the loud singleton. Moreover, the effect of the quiet singletons in this experiment (M = 30 ms) was not smaller than the effect of the loud singletons in Experiment 1A (M = 29 ms).

As before, there was no effect of target presence on the RTs ($F(1, 7) = 3.55$, MSE $= 1910.89$, $p = .10$) but there was a significant interaction between singleton presence and target presence ($F(1, 7) = 10.52$, MSE $= 904.35$, $p < .05$), such that the singleton effect was pronounced on target absent trials but did not occur on target present trials (see Table 1).

Errors. No main effects or interactions reached significance in the error ANOVA ($p > .10$ for all effects). However error rates show trends consistent with the RT results, as shown in Table 1.

Experiment 2

Experiments 1A and 1B have found interference effects due to irrelevant singleton distractors of both higher and lower intensity than the other nontargets. In the following two experiments, we asked whether these interference effects could generalise to singletons that are unique on the dimension of frequency.

Targets were now defined on the basis of intensity. For half the participants, targets were louder than nontargets. For the other half, targets were quieter than nontargets. On half of the trials in Experiment 2A one of the nontargets was presented at a higher frequency than the rest of the sounds. In Experiment 2B, this irrelevant singleton was of lower frequency than the other sounds.

Method

Participants. Eight new participants took part in Experiment 2A, and a further eight participants took part in Experiment 2B.

Stimuli and Procedure. Targets in the present experiment were defined by intensity, being louder (approximately 83 dB SPL) than nontargets (approximately 72 dB

SPL) for half of the participants and quieter (approximately 72 dB SPL) than nontargets (approximately 83 dB SPL) for the other half of the participants. The singleton distractor was presented at the nontarget intensity with a frequency that was higher (520 Hz) than the rest of the sounds (440 Hz) in Experiment 2A and lower (440 Hz) than the rest of the sounds (520 Hz) in Experiment 2B. All other aspects of the method were the same as in Experiment 1A.

Results and Discussion

Experiment 2A

RTs. Table 2 presents mean RTs and error rates across participants as a function of singleton presence (vs. absence) and target presence (vs. absence). The RT ANOVA revealed a significant effect of singleton presence ($F(1, 7) = 9.37$, MSE = 946.72, $p < .05$). Consistent with the findings of both previous experiments, target RTs were slower when the singleton was present than when it was absent, as can be seen in Table 2. This finding suggests that irrelevant singleton distractors defined by frequency can capture attention, disrupting performance on the detection task. Again, there was no significant effect of target presence in the RTs ($F(1, 7) < 1$). In this experiment the singleton cost did not interact with target presence, ($F(1, 7) = 3.79$, MSE = 164.96, $p = .09$) although the numerical trend was for a greater cost when the target was absent (vs. present) as before (see Table 2).

Errors. There was no significant effect of singleton presence in the error ANOVA, nor was there a significant interaction between singleton and target presence ($p > .10$ for both comparisons). However error rates show trends consistent with the RT results, as shown in Table 2. There was a trend towards a significant effect of target presence in the error rates, (F (1, 7) = 4.28, MSE = .00205, p = .08). As was the case in Experiment 1A, this effect indicated that participants tended to have more misses than false alarms.

-------------- Table 2 about here ---------------

Experiment 2B

RTs. Table 2 presents mean RTs and error rates across participants as a function of singleton presence (vs. absence) and target presence (vs. absence). In line with the findings of all three previous experiments, the RT ANOVA revealed a significant effect of singleton presence (F (1, 7) = 14.37, MSE = 722.08, p < .01) indicating that target responses were slower when the singleton was present versus absent (see Table 2). The effect of the low frequency singletons in this experiment (M = 36 ms) was similar to the effect of the high frequency singletons in Experiment 2A (M = 33 ms).

There was also a significant effect of target presence (F (1, 7) = 18.06, MSE = 835.96, p < .01) indicating slower responses on target absent vs. target present trials. Once again there was an interaction between singleton presence and target presence (F (1, 7) = 9.08, MSE = 805.92, p < .05) indicating, that the singleton produced interference when the target was absent but not when it was present (t (7) < 1, see Table 2).

Errors. The error ANOVA revealed no significant main effects (p > .10 for both comparisons). However, as can be seen in Table 2, there was a trend towards an interaction between singleton presence and target presence (F (1, 7) = 5.09, MSE = .00141, p < .06), indicating stronger singleton interference on target absent trials than on target present trials, in line with the RT results.

In conclusion, the presence of an irrelevant auditory feature singleton has produced a cost to performance in all four of the previous experiments. The singleton effect has generalised across singletons of high and low intensity and high and low frequency, relative to the other sounds. In all four experiments singleton effects were greater when the target was absent than when it was present. In fact in some cases singleton effects were only found when the target was absent. As discussed earlier (in the Results and Discussion of Experiment 1A) the reduced or eliminated singleton cost on target present trials may be due to competition for attention between the target and distractor.

Experiment 3

Because detection tasks are based on the presence or absence of an odd sound (i.e. the target), Experiments 1 - 2 are open to the criticism that participants might have searched for the presence of any odd sound rather than focusing search upon the relevant target feature, and would thus have been particularly prone to capture by the singleton distractors. In Experiments 3-4, we used a discrimination task in which a target was always present and participants had to indicate which of two possible targets had appeared (see Theeuwes, 1992, for a similar modification of the visual search task). In this task, a unique target sound is present on each trial. Thus the task involves discrimination of an exact feature on the target dimension and the presence of a unique sound alone cannot inform the participant of the correct response. As in the previous experiments, a feature singleton, defined on an irrelevant dimension, was presented on 50% of trials and target performance was analysed as a function of singleton presence versus absence.

In Experiments 3A and 3B, participants searched sequences of five sounds for targets that were defined as being either higher or lower in frequency than the nontargets. A target was present on each trial and participants were asked to respond according to which of the two possible targets had appeared. Singletons were presented on half the trials at the nontarget frequency and differed from nontargets on the irrelevant dimension of intensity, being of higher intensity than the other sounds in Experiment 3A and lower intensity than the other sounds in Experiment 3B.

Method

Participants. Ten new participants took part Experiment 3A, one of whom was replaced due to chance level performance (50% errors). A further eight participants took part in Experiment 3B. Four of these participants were replaced due to an error rate that was over 3 SDs from the group mean (group M = 6.0%, SD = 4.03%).

Apparatus and stimuli. The equipment used was the same as described for Experiment 1A. High targets had frequencies of 520 Hz, low targets 440 Hz and nontargets had intermediate frequencies of 480 Hz. Singletons were presented at the nontarget frequency (480 Hz). In Experiment 3A singletons were of higher intensity (approximately 83 dB SPL) than targets and nontargets (approximately 72 dB SPL). In Experiment 3B singletons were of lower intensity (approximately 72 dB SPL) than targets and nontargets (approximately 83 dB SPL). Stimulus durations and ISIs were the same as in Experiment 1A.

Design and Procedure. The design and procedure were similar to those of Experiment 1A, with the following exceptions. The stream of sounds included five rather than four sounds. A target appeared on every trial in either the third or fourth position with equal probability. Participants were told that a target would always be present, and pressed “1” or “2” on the number keypad at the end of each stream according to which of the two possible targets they had heard. Targets were just as likely to be of high frequency as of low. The irrelevant distractor singleton appeared on 50% of trials, directly before or after the target with equal probability. A 96 trial block included a fully counterbalanced random mix of the factors of singleton presence, singleton position and target position and their combinations. Two practice blocks of 16 trials each preceded the experimental blocks.

Results and Discussion

Experiment 3A

RTs. Table 3 presents mean RTs and error rates across participants as a function of singleton presence (vs. absence). A one-way ANOVA with the within-subjects factor of singleton presence (present vs. absent) revealed a significant main effect ($F (1, 9) = 7.88$, MSE = 453.30, $p < .05$). As in all previous experiments, target RTs were slower on singleton present trials than on singleton absent trials, in line with predictions of AC by the irrelevant singleton distractor (see Table 3). A further one-way within-subjects ANOVA was conducted on the RTs from singleton-present trials with the factor of singleton position (before vs. after the target). In this ANOVA there was no effect of singleton position, (M = 322 ms for both singleton positions, $F (1, 9) < 1$).

Errors. The error ANOVA revealed no significant effect of singleton presence ($F (1, 9) = 1.15$, MSE = .00157, $p = .31$), although the numerical trend was similar to that shown in the RTs (see Table 3). There was no effect of singleton position (before (M = 12%) vs. after the target (M = 10%), $F (1, 9) < 1$).

--------------- Table 3 about here ---------------

Experiment 3B

RTs. Table 3 presents mean RTs and error rates across participants as a function of singleton presence (vs. absence). As in all our previous experiments, the RT ANOVA revealed a significant main effect of singleton presence ($F(1, 7) = 10.41$, MSE = 65.77, $p < .05$), reflecting slower target RTs on singleton present vs. singleton absent trials (see Table 3). This suggests, in support of Experiment 1B, that the presence of a unique auditory feature distractor captures attention even when it is of lower intensity than the other sounds. The analysis of singleton present trials revealed no effect of singleton position in the RTs (before (M = 261 ms) vs. after the target (M = 263 ms), $F(1, 7) < 1$).

A mixed model ANOVA comparison of the effects of singleton presence between Experiment 3A and Experiment 3B found no interaction ($F(1, 16) = 1.46$, MSE = 283.76, $p = .25$). This indicates that the trend suggested by the overall means for a larger singleton effect due the high intensity singletons used in Experiment 3A (M = 27 ms) than to the low intensity singletons used in the present experiment (M = 13 ms) was not shown consistently across participants. Although the present experiment clearly shows a significant interference effect due to a singleton of lower intensity than the other sounds, it is interesting to note that the numerical trends suggest, in line with Experiments 1A and 1B, that the high intensity singletons used in Experiment 3A have a stronger effect than the low intensity singleton used here. This is presumably due to the fact that singletons of high intensity are more salient than those of low intensity (see Theeuwes, 1991, 1992, 1994).

Errors. The error ANOVA found no effect of singleton presence ($F(1, 7) < 1$). However there was a small but significant effect of singleton position ($F(1, 7) = 7.62$, $MSE = .00064$, $p < .03$) reflecting higher error rates when the singleton occurred before ($M = 8\%$) vs. after the target ($M = 5\%$). In fact, the error rate when the singleton appeared after the target was similar to the singleton absent condition ($M = 6\%$). This result is perhaps unsurprising, as when the singleton occurs before the target, AC is more likely to disrupt target perception than when the singleton occurs after the target (and early perceptual processing of the target has progressed without competition). Note however that AC by singletons occurring after the target disrupted RTs just as much as AC by singletons occurring before the target, suggesting that singleton position is only critical for finding effects of AC on errors.

Experiment 4

Experiments 3A and 3B found significant interference by intensity singletons in frequency discrimination tasks. The purpose of Experiments 4A and 4B was to examine whether intensity discrimination tasks would be similarly affected by singleton distractors defined on the irrelevant dimension of frequency. Participants in the present experiments searched for a target sound that was always present and responded according to whether it was of higher or lower intensity than the intermediate nontargets. Singletons were presented at the same intensity as the nontargets, with a higher frequency than targets and nontargets in Experiment 4A and a lower frequency in Experiment 4B.

Method

Participants. Eight new participants took part in Experiment 4A and a further eight took part in Experiment 4B.

Stimuli and Procedure. Targets in the present experiment were defined by intensity, being of higher (approximately 83 dB SPL) or lower intensity (approximately 72 dB SPL) than the intermediate nontargets (approximately 78 dB SPL). The singleton distractor was of the same intensity as the nontargets with a frequency that was higher (520 Hz) than the rest of the sounds (440 Hz) in Experiment 4A and lower (440 Hz) than the rest of the sounds in Experiment 4B. All other aspects of the method were the same as in Experiment 3A.

Results and Discussion

Experiment 4A

RTs. Table 4 presents mean RTs and error rates across participants as a function of singleton presence (vs. absence). The RT ANOVA revealed a significant main effect of singleton presence ($F(1, 7) = 10.16$, MSE = 1198.11, $p < .05$), indicating slower target RTs in the presence versus absence of the singleton distractor, as shown in Table 4. The analysis of singleton present trials did not find a significant effect of singleton position in the RTs, although there was a small numerical trend for a larger effect for singletons occurring before (M = 334 ms) versus after the target (M = 295), ($F(1, 7) = 3.81$, MSE = 1569.72, $p = .09$).

Errors. The error ANOVA found a significant main effect of singleton presence ($F(1, 7) = 15.72$, MSE = .00129, $p < .01$), reflecting higher error rates on singleton present versus singleton absent trials (see Table 4). There was also a significant effect of singleton position ($F(1, 7) = 12.92$, MSE = .00534, $p < .01$). As in Experiment 3B, error rates were greater when the singleton occurred before (M = 24%) versus after the target

(M = 11%) and error rates in the singleton after condition were similar to error rates in the singleton absent condition (M = 10%).

--------------- Table 4 about here ---------------

Experiment 4B

RTs. Table 4 presents mean RTs and error rates across participants as a function of singleton presence (vs. absence). As in all previous experiments, the RT ANOVA found a significant main effect of singleton presence ($F(1, 7) = 17.11$, MSE = 345.11, $p < .01$), indicating slower target RTs on singleton present trials than on singleton absent trials (see Table 4). The analysis of singleton present trials revealed no effect of singleton position in the RTs (before (M = 296 ms) vs. after the target (M = 282 ms), $F(1, 7) = 1.08$, MSE = 703.24, $p = .33$).

In a mixed model ANOVA comparison of the effects of singleton presence between Experiment 4A and Experiment 4B there was no difference ($F(1, 14) <1$) between the effect of the high frequency singletons used in Experiment 4A (M = 55 ms) and the effect of the low frequency singletons in the present experiment (M = 39 ms).

Errors. The error ANOVA also revealed a significant effect of singleton presence ($F(1, 7) = 7.93$, MSE = .00091, $p < .05$). Consistent with the RTs error rates were higher on singleton present versus singleton absent trials, as can be seen in Table 4. There was also a significant effect of singleton position ($F(1, 7) = 13.05$, MSE = .00161, $p < .01$), suggesting, in line with Experiments 3B and 4A, that error rates were higher when the singleton occurred before (M = 20%) vs. after the target (M = 13%) with error rates in the latter condition similar to those in the singleton absent condition (M = 12%).

In conclusion, the results of Experiments 3-4 demonstrate that irrelevant intensity or frequency singletons can interfere with an auditory search task in which a target sound is present on every trial. This is important because Experiments 1-2 used a search task that involved detection of the presence or absence of an odd sound, and it is therefore possible that participants in those experiments searched for the presence of any unique sound rather than focusing on the specific target feature. Because in Experiments 3-4 a unique target sound was present on each trial, the presence of a unique sound alone could not inform the participant of the correct response. Nevertheless, the presence of a singleton sound interfered with target responses. These findings thus strengthen our claim that such singletons capture attention despite being clearly irrelevant to the task. Experiments 3-4 are also important in establishing that AC can be consistently found in the presence of the target (recall that the singleton effects in Experiments 1-2 were stronger on target absent vs. target present trials).

Experiment 5

The previous experiments have found significant cost to both target detection and discrimination tasks associated with the presence of an irrelevant feature singleton. Although these results are encouraging for the hypothesis that irrelevant auditory singletons can capture attention, there is an alternative account of the findings so far. As reviewed in the general introduction, people's attention can be cued towards ranges of frequencies, intensities and durations (e.g. Mondor & Bregman, 1994; Mondor & Lacey, 2001; Scharf et al., 1987). For example, participants are better at judging the duration of a target sound if it is preceded by a cue of the same frequency rather than a cue of a different frequency, even though frequency is irrelevant to the task (Mondor & Bregman, 1994). This presents a potential problem for the discrimination tasks we have used, as they could have been carried out by comparing the target with the sound directly before it (and perhaps also the sound after it). Thus the interference effect we observe might be due to the fact that it is harder to compare the target with a singleton sound than with an ordinary nontarget sound, because the singleton sound varies on an irrelevant dimension whereas the ordinary nontarget does not.

The present experiment was designed to investigate this potential alternative account. In a change from previous experiments, we compared the interference effect of singletons that were presented directly before or after the target, with the effect of singletons that were separated from the target by an intervening nontarget. If the singleton interference we have shown previously was due to the difficulty of comparing the target with a singleton sound (versus comparing the target with a nontarget sound) then it should be eliminated when the singleton is separated from the target by an intervening nontarget. However, if the interference was due to AC as we claim, then the effect should persist despite such separation.

In addition, we sought to generalise the effects over another dimension for the relevant task. We now asked participants to search for a target defined by duration. Singletons were defined by frequency, being lower than the other sounds, and were present on 50% of trials.

Method

Participants. 10 new participants took part in the experiment.

Stimuli. Targets were defined on the basis of duration. Nontargets had durations of 100 ms, long targets lasted 150 ms, and short targets lasted 50 ms. Singletons were presented at the nontarget duration (100 ms) and were of lower frequency (440 Hz) than targets and nontargets (which were at 520 Hz). All sounds had intensities of approximately 78 dB SPL. The duration of the inter-stimulus intervals (ISIs) was varied to ensure that the total duration of stimulus presentation and ISI was kept constant at 185 ms. for all sound durations.[6]

Procedure. Participants searched a sequence of seven sounds for a target tone of longer or shorter duration than the non-target tones. A target appeared on every trial in either the fourth or fifth position with equal probability, and was just as likely to be longer in duration than the non-targets as shorter. Participants were informed that the target would always be present and were asked to respond either “1” for “short target” or “2” for “long target”. The singleton distractor appeared on 50% of trials, either before or after the target with equal probability. On half of these singleton present trials, the singleton was directly before or after the target (we refer to this as a singleton-target separation of 0). On the other half, the singleton was separated from the target by an intervening nontarget (corresponding to a singleton-target separation of 1). A 96 trial block included a fully counterbalanced random mix of the following factors and their combinations: target position, singleton presence, singleton position (before or after the target) and singleton-target separation (0 or 1). Six experimental blocks were run, preceded by a single practice block of 24 trials. All other aspects of the method were as described in Experiment 1A.

Results and Discussion

RTs. Table 5 presents mean RTs and error rates across participants as a function of singleton condition (absent; present separation 0; present separation 1). A one-way

ANOVA with the within-subjects factor of singleton presence (vs. absence) revealed a significant main effect (F (1, 9) = 9.58, MSE = 391.18, $p < .05$). In line with previous results, target RTs were slower in the presence vs. the absence of the singleton distractor, suggesting that the singleton captured attention (see Table 5). A further two-way ANOVA on RTs from singleton present trials with the within-subjects factors of singleton-target separation (0 vs. 1) and singleton position (before vs. after) found no significant main effect of singleton-target separation (F (1, 9) = 1.19, MSE = 921.80, p = .30). As can be seen in Table 5, the interference associated with singleton presence was just as strong for singletons that were separated from the target by an intervening nontarget as for singletons that appeared directly before or after the target. Thus the singleton effects are unlikely to be due to the comparison between the target and the sound preceding it being more difficult when that sound was different to the rest of the nontarget sounds. There was no effect of singleton position (before (M = 331 ms) vs. after the target (M = 327 ms), F (1, 9) < 1) and no interaction between singleton-target separation and singleton position (F (1, 9) = 2.33, MSE = 871.99, p = .16). Mean RTs were 319 ms and 326 ms for singleton before and after the target (respectively) with a singleton-target separation of 0; mean RTs were 343 ms and 322 ms for singleton before and after the target (respectively) with a singleton-target separation of 1.

Errors. The error ANOVA revealed a significant effect of singleton presence (F (1, 9) = 7.36, MSE = 6.11, $p < .05$), such that error rates were higher when the singleton was present (vs. absent), consistent with the RTs (see Table 5). Table 5 also shows that, as in the RT analysis, there was no difference between the effects on error rates of singletons with a separation of 0 and those with a separation of 1 (F (1, 9) = 1.34, MSE =

9.04, p = .28). As in previous experiments, there was a significant main effect of singleton position in the error rates (F (1, 9) = 8.69, MSE = 42.82, p < .05): participants were less accurate when the singleton appeared before the target (M = 13%) as opposed to after the target (M = 7%) with the latter condition resulting in the same number of errors as the target absent condition (M = 7%). The interaction between singleton-target separation and singleton position was not significant (F (1, 9) = 2.20, MSE = 24.07, p = .17). Mean error rates were 12% and 8% for singleton before and after the target (respectively) with a singleton-target separation of 0; mean error rates were 15% and 7% for singleton before and after the target (respectively) with a singleton-target separation of 1.

--------------- Table 5 about here ---------------

In sum, Experiment 5 has demonstrated that singleton interference persists when the singleton is separated from the target by an intervening nontarget. This rules out an explanation for singleton interference in terms of it being harder to compare a target with a singleton than with a nontarget. Experiment 5 has also generalised the singleton effects of previous experiments to a task in which targets are defined by duration.

Experiment 6

Experiments 1-4 found a significant cost to both target detection and discrimination tasks associated with the presence of an irrelevant feature singleton. Experiment 5 ruled out the possibility that singleton interference in the discrimination task in Experiments 3-4 was due to the difficulty of comparing the target with a singleton sound, versus comparing the target with a nontarget sound. These findings provide preliminary evidence for AC by auditory feature singleton distractors.

We have argued that the interference observed in Experiments 1-5 is due to the irrelevant singleton feature capturing attention: because the singleton feature in these experiments was always presented within a distractor sound, AC was always harmful to performance as it always drew attention to an irrelevant item. An important prediction of the AC account is that capture should facilitate performance if the irrelevant singleton feature occurs within the target sound, as the irrelevant singleton should then draw attention to a relevant item. For example, Jonides and Yantis (1988) asked participants to search a visual array for a target letter among other letters. They found that the irrelevant singleton feature of abrupt-onset interfered with search if it coincided with a distractor but facilitated search if it coincided with the target. In Experiment 6 we asked whether the interference effects from an irrelevant auditory feature singleton could reverse into facilitation when the irrelevant singleton coincides with the target rather than a distractor sound.

As in Experiment 5, we defined singletons by their frequency and targets by their duration. Although the interaction between the dimensions of frequency and intensity should not be noticeable over the particular ranges used here (see Footnote 3), any slight interaction could complicate interpretation of the effects of the singleton feature when it occurs within the target sound. We therefore thought it would be desirable to demonstrate a facilitation effect using the dimensions of duration and frequency, as these dimensions are known to be independent (e.g. Allan & Kristofferson, 1974; Woods, Sorkin & Boggs, 1979).

We used a discrimination task in which participants searched for a target that was present on each trial, and responded according to whether it was of long or short duration. Nontargets were of intermediate duration. An irrelevant higher frequency singleton feature was presented on two thirds of the trials. In a change from previous experiments the target sound itself contained this singleton feature on a third of trials. On another third of trials the singleton feature was presented in a nontarget sound (as in previous experiments). The singleton feature was absent from the sequence on the remaining third of trials. We predicted that the presence (vs. absence) of a nontarget singleton would interfere with performance of the discrimination task as before. By contrast, the presence of a singleton that coincided with the target sound should lead to facilitation of performance, by comparison with singleton-absent trials.

Method

Participants. 18 new participants took part in the experiment. One subject was replaced due to an error rate that was over 3 SDs higher than the group mean (group M = 8%, SD = 6.9%).

Stimuli. The stimuli were the same as in Experiment 5, except that the singleton feature was high frequency (520 Hz) relative to the other sounds (440 Hz).

Procedure. Participants searched a sequence of five sounds for a target tone of longer or shorter duration than the nontarget tones. Targets appeared on every trial and were equally likely to be longer or shorter than the non-targets. Targets appeared in either the third or fourth position with equal probability. On a third of the trials the targets were presented with the irrelevant high frequency singleton feature. On another third of trials this singleton feature coincided with a distractor (directly before or after the target with equal probability). On the remaining third of trials the singleton feature was absent from the search array. A 96 trial block included a fully counterbalanced random mix of the factors of singleton condition, target position and their combination. All other aspects of the procedure were the same as in Experiment 5.

Results and Discussion

RTs. Table 6 presents mean RTs and error rates across participants as a function of singleton condition. A one-way ANOVA with the within-subjects factor of singleton condition (absent; present in target; present in distractor) found a significant main effect (F (2, 34) = 11.98, MSE = 1039.50, $p < .01$). F-contrasts revealed that, by comparison with the singleton absent condition, RTs were significantly slower when the high frequency singleton feature coincided with a distractor sound (F (1, 17) = 4.64, MSE = 2845.50, $p < .05$) and significantly faster when the singleton feature coincided with the target sound (F (1, 17) = 7.98, MSE = 1469.72, $p < .05$), as shown in Table 6. These findings provide support for the hypothesis that the irrelevant singleton feature captures attention, leading to interference if the object to which attention is drawn is irrelevant and facilitation if the object is relevant. In a one way ANOVA of RT in the singleton ‘present in distractor’ condition with the factor of singleton position there was no significant effect of singleton position although the numerical trend was for slower responses for singleton distractor before (M = 351 ms) versus after the target (M = 333 ms), F (1, 17) = 3.13, MSE = 1012.32, $p = .10$.

Errors. In line with the RT analysis there was a significant main effect of singleton condition ($F(2, 34) = 17.98$, MSE = .00227, $p < .01$). Also as in the RT analysis, F contrasts revealed that, by comparison with the singleton absent condition, error rates were greater when the singleton feature coincided with a distractor ($F(1, 17) = 5.8$, MSE = .00203, $p < .05$) and smaller when the singleton feature coincided with the target ($F(1, 17) = 19.65$, MSE = .00407, $p < .01$, see Table 6).

As in previous experiments there was a significant effect of singleton distractor position in the error rates ($F(1, 17) = 18.15$, MSE = .00467, $p < .01$) indicating that responses were less accurate when the singleton distractor occurred before ($M = 18\%$) versus after the target ($M = 8\%$), with the latter condition resulting in similar error rates to the singleton absent condition ($M = 7\%$).

In conclusion, Experiment 6 has replicated the findings of Experiments 1-5 in demonstrating a significant cost, in both RTs and errors, due to the presence of an irrelevant singleton feature within one of the nontargets in an auditory search task. Importantly, the singleton interference effect reversed into facilitation of responses when it was presented within the same sound as the target. This is an important finding, as an account of the interference results in terms of AC predicts facilitation of this sort. Notice that such facilitation effects cannot be explained in terms of expectancy, as the target is less expected when it appears at the singleton frequency (33% of trials, vs. 66% for nontarget frequency) and yet performance is facilitated in this condition.

Our finding of facilitation effects in the present experiment may also appear to be inconsistent with Schröger and Wolff’s (1998) finding that target detection is worse when the target itself is a frequency deviant. However, this apparent discrepancy is likely to be due to the different designs of the two tasks. Our tasks involved searching for a target sound within a RSAP stream. In this design, stimuli must compete against each other for attentional resources and AC by the target stimulus will provide it with a processing advantage. By contrast, stimuli in Schröger and Wolff's (1998) study were separated by intervals of one second and thus did not have to compete with each other for attention. The interference in responses to targets of unexpected frequency in their task may thus be due to the effects of expectancy rather than capture of attention.

--------------- Table 6 about here ---------------

General discussion

The present experiments have found significant behavioural costs in auditory search tasks due to the presence of an irrelevant feature singleton. This finding has generalized across singletons of high and low frequency as well as high and low intensity, and across search tasks involving detection of whether the target was present or absent (as in typical visual search tasks) as well as tasks involving discrimination between two targets, one of which is always present (similar to the visual search tasks used in Theeuwes's AC studies, e.g. Theeuwes, 1992).

The singleton interference observed is unlikely to be due to some lower-level interactions between adjacent sounds as it was also found when the target and the singleton were separated by another sound. Moreover, the finding that the interference effects due to singleton distractors reversed into facilitation when the singleton feature was presented within the target rules out alternative accounts in terms of any general property of the singleton feature that causes it to be distracting (for example being of lower probability then the rest of the sounds), as the same singleton feature can cause either interference of facilitation depending on whether it is presented within a nontarget or a target sound. Thus our findings are best explained in terms of AC by the singleton sound and converge overall to provide a demonstration of AC in the auditory domain.

Implications for Visual Research

Our findings of auditory AC are consistent with previous visual search studies that have demonstrated behavioural cost or facilitation effects associated with AC by irrelevant singletons depending on whether they coincide with a target or a nontarget stimulus (e.g. Jonides & Yantis, 1988; Pashler, 1988; Theeuwes, 1992; Yantis & Jonides, 1984; Yantis & Jonides, 1990). The singletons in our study were completely irrelevant to the tasks as they were defined on a different dimension from the target and did not predict the target in any way. Our results therefore agree with the visual search studies of Pashler (1988) and Theeuwes (1991, 1992) that singletons can capture attention even when they are made irrelevant to the task.

Some previous visual search studies have suggested that bottom up factors such as the relative salience of the target feature compared with the irrelevant singleton feature can be important determinants of visual AC (for review see Theeuwes, 1994). As we did not systematically manipulate the salience of singleton and target features, our data speak only indirectly to this issue. However we found no evidence for a specific role of relative salience of the singleton feature compared with the target feature, as singleton interference was found in all our experiments irrespective of the particular combination of target and singleton features. Perhaps, then, hearing is especially prone to attentional capture because of its role as an early warning system, and thus stimulus salience may be less important in determining auditory AC. This would be an interesting topic for further investigation.

Our findings of auditory AC in temporal search arrays have an interesting implication for visual search. Recall that, as most previous research into focused auditory attention has used temporal arrays (perhaps because spatial location information is processed with lower priority than other sound attributes such as frequency, e.g. Woods et al., 2001), we used rapid serial auditory presentation (RSAP) search arrays rather than the spatial arrays typically used in the visual research. Our findings of auditory AC within these temporal arrays thus provide evidence that attention can be captured to an object that is differentiated from other objects in terms of temporal position rather than spatial location. It would be interesting to ask whether a similar temporal AC effect can be found in the visual domain, i.e. whether the presence versus absence of an irrelevant visual singleton (e.g. a red nontarget among green) in a rapid serial visual presentation (RSVP) stream will capture attention from a target task based on another dimension (e.g. shape). Previous studies within the "attentional blink" paradigm have shown that targets presented in RSVP streams can produce a cost to detection of subsequent targets in the stream (for review see Shapiro & Terry, 1998). The results of our RSAP tasks suggest that irrelevant visual singleton distractors might produce costs to target detection in RSVP tasks, as these visual singletons should capture attention and the phenomenon of "attentional blink" is thought to depend on allocation of attention to the target. Such questions are currently under investigation in our lab.

Implications for Auditory Research

Previous research has suggested that auditory attention can be focused on particular ranges of frequencies, intensities or durations at the expense of stimuli that fall outside the unattended range (e.g. Greenberg & Larkin, 1968; Luce & Green, 1978; Mondor & Bregman, 1994; Mondor & Lacey, 2001; Mori & Ward, 1991, 1992; Nosofsky, 1983; Schröger and Wolff, 1998; Scharf et al., 1987; Tanner & Norman, 1954; Yama & Robinson, 1982). However the present results have shown that such attentional focusing is not always entirely successful, as it can be disrupted by the presence of singleton distractors, even when they are completely irrelevant to the task at hand.

Although very few studies have looked at the effects of singleton distractors on auditory search tasks, there has been extensive ERP research into the effects of sounds that form a change in a repetitive auditory sequence. Such deviant sounds have been shown to elicit an ERP component termed the mismatch negativity (MMN) that occurs about 100 ms after onset (e.g. Näätänen, 1975; Näätänen, Gaillard & Mäntysalo, 1978, 1980; Näätänen, 1979; Näätänen & Gaillard, 1983; reviewed by Näätänen, 1992). Unfortunately, these studies have not often examined the behavioural effects of the presence of a deviant sound and in any case there are several differences that prevent direct comparison between the MMN research and the present study. First, our tasks consist of short sequences of rapidly presented sounds designed to be perceived as single search arrays, each requiring a response. In contrast, the MMN experiments usually involve constant exposure to much longer sequences that typically contain several hundred stimuli. ISIs are also often considerably longer in MMN tasks than in our study, with typical ISIs ranging from 300-1000 ms (compared with 50 ms in our experiments).

As we have argued earlier, competition for attention is less likely to occur in such circumstances. Second, in our tasks there are often two “deviant” sounds (both target and singleton) in a four or five sound sequence, typically occurring one after another. Thus it is unlikely that they would be treated as deviants to the same extent as the odd sounds used in the MMN studies, as these occur much less frequently. For both these reasons, the MMN research does not seem directly applicable to our findings. Finally, it is important to note that the singleton stimuli in our experiments were specified as completely irrelevant to the task. Participants were aware that such singletons might occur and that it might harm their performance if they failed to ignore them. In contrast, very few of the MMN studies actively encourage participants to ignore the deviant sounds (other than by providing them with another task such as reading a book). Interestingly the few studies that have encouraged participants to focus attention strongly away from the deviant sounds have found that this can reduce or even eliminate the MMN, (e.g. Trejo, Ryan-Jones & Kramer, 1995; Woldorff, Hackley & Hillyard, 1991; Woldorff, Hillyard, Gallen, Hampson & Bloom, 1998). However these studies have used either dichotic listening tasks or more complex semantic tasks, and as such are not directly comparable with our experiments.

Although the differences between the MMN paradigm and our design prevent direct comparison, our results nevertheless suggest that the deviant sounds used to elicit the MMN ought to interfere with behaviour in an ongoing task. Interestingly, we would also predict facilitation due to the deviant sound when it coincides with a target sound, as long as the task involves RSAP search (cf. Schröger & Wolff, 1998).

Implications for Crossmodal Research

Although the present study has focused on establishing AC solely in hearing, our finding that auditory AC shares some of the characteristics of visual AC suggests that at least some AC effects may not depend on stimulus modality. Indeed Spence and Driver (1997) found some evidence that AC can be obtained crossmodally. They asked participants to judge the elevation of either auditory or visual targets, presented to one side or another. Responses were faster and more accurate for both visual and auditory targets when they were preceded by auditory cues on the same rather than the opposite side (at intermediate elevation), suggesting that these cues had captured attention despite being valid on only 50% of trials. However as the cues in this study were presented on their own they did not have to compete for attention with other objects. Thus the results cannot inform about the extent to which a singleton stimulus captures attention when in competition with multiple other stimuli, as in visual and auditory search tasks (such as the one used here). It would thus be interesting to ask whether cross modal AC effects can be found for auditory (or visual) singletons presented during performance of a visual (or auditory) search task.

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Footnotes

Note 1. The phenomenon of AC in general has also been studied using the spatial cuing paradigm (e.g. Jonides, 1980, 1981; Müller & Rabbitt, 1989; Remington, Johnston & Yantis, 1992). However the objects (cues) that have been shown to capture attention in these tasks were typically presented on their own (c.f. Folk & Remington, 1998; Folk, Remington & Johnston, 1992; Folk, Remington & Wright, 1994; Gibson & Kelsey, 1998; Johnson, Hutchison & Neill, 2001) and therefore did not have to compete for attention with other objects. Thus these studies cannot inform about the extent to which a singleton stimulus captures attention when in competition with multiple other stimuli as in visual search.

Note 2. Abrupt onset may be an exception as abrupt-onset singletons have been found to capture attention even in difficult search tasks where the target is not a feature singleton (e.g. where the target is defined as a particular letter among other letters). Colour and intensity singletons do not interfere in this type of search (e.g. Jonides & Yantis, 1988).

Note 3. The ranges of frequencies (440 Hz-520 Hz) and intensities (72 dB SPL-83 dB SPL) used in this experiment as well as all following experiments were also chosen to minimize any effects of interaction between the two dimensions. Although sounds of a high frequency are perceived as louder than sounds of a low frequency when the two are presented with the same intensity (e.g. Robinson & Dadson, 1956), such interactions between the dimensions would not be noticeable over the ranges used here.

Note 4. A preliminary mixed model ANOVA with the between-subjects factor of target type revealed no significant interactions involving target type and singleton presence, for all the detection experiments (Experiments 1-2). For this reason the results are reported pooled across target type in all these experiments.

Note 5. Because Experiments 1-2 used a detection design, in which the target was absent on 50% of the trials and could appear in one of three possible positions when it was present, there were not enough observations for each target position to allow a reliable analysis of singleton position (before vs. after the target).

Note 6. Pilot testing had suggested that a design in which all sounds were followed by the same length ISI (as in the previous experiments) was very confusing for participants, as sounds were perceived to appear in irregular temporal positions.

Table 1

Averages of participants' mean RTs in ms (RT) and mean error rates (%E), with standard errors (SE) for Experiments 1A and 1B, as a function of target and singleton presence

		Singleton condition				Effect size	
		Absent (A)		Present (P)		(P-A)	
Experiment	Target	RT	%E	RT	%E	RT	%
1A	Absent	240	1	290	2	50	1
	Present	251	1	261	4	10	3
1B	Absent	295	1	360	6	65	5
	Present	300	3	297	3	-3	0

Note. All errors under target absent conditions are "false alarms" and all errors under target present conditions are "misses".

Table 2

Averages of participants' mean RTs in ms (RT) and mean error rates (%E), with standard errors (SE) for Experiments 2A and 2B, as a function of target and singleton presence

		Singleton condition				Effect size	
		Absent (A)		Present (P)		(P-A)	
Experiment	Target	RT	%E	RT	%E	RT	%
2A	Absent	262	3	305	4	43	1
	Present	264	5	288	8	24	3
2B	Absent	310	5	376	9	66	4
	Present	297	9	303	7	6	-2

Note. All errors under target absent conditions are "false alarms" and all errors under target present conditions are "misses".

Table 3

Averages of participants' mean RTs in ms (RT) and mean error rates (%E), with standard errors (SE) for Experiments 3A and 3B, as a function of singleton presence

	Singleton condition				Effect size	
	Absent (A)		Present (P)		(P-A)	
Experiment	RT	%E	RT	%E	RT	%
3A	295	9	322	11	27	2
3B	249	6	262	6	13	0

Table 4

Averages of participants' mean RTs in ms (RT) and mean error rates (%E), with standard errors (SE) for Experiments 4A and 4B, as a function of singleton presence

	Singleton condition				Effect size	
	Absent (A)		Present (P)		(P-A)	
Experiment	RT	%E	RT	%E	RT	%
4A	257	10	312	17	55	7
4B	251	12	289	16	38	4

Table 5

Averages of participants' mean RTs in ms (RT) and mean error rates (%E), with standard errors (SE) for Experiment 5, as a function of singleton condition

Singleton absent (A)		Singleton present Separation 0 (P0)		Effect size (P0-A)		Singleton present Separation 1 (P1)		Effect size (P1-A)	
RT	%E	RT	%E	RT	%E	RT	%E	RT	%E
299	7	322	10	23	3	333	11	34	4

Table 6

Averages of participants' mean RTs in ms (RT) and mean error rates (%E), with standard errors (SE) for Experiment 6, as a function of singleton condition

Singleton absent (A)		Singleton present in target (PT)		Facilitation effect size (A-PT)		Singleton present in distractor (PD)		Distraction effect size (PD-A)	
RT	%E	RT	%E	RT	%E	RT	%E	RT	%E
314	7	288	4	26	3	341	13	27	6