For my father, John Dalton

Attentional capture in hearing: Effects of irrelevant singleton sounds on auditory search

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Abstract

The phenomenon of attentional capture by a unique yet irrelevant "singleton" distractor has typically been studied in visual search. In this thesis I ask whether attention can also be captured by auditory singletons in tasks of auditory search. 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 demonstrate attentional capture in the auditory domain. Further experiments showed that, like visual attentional capture, auditory attentional capture depends on participants adopting an "odd-one-out" strategy for attentional allocation. In addition, a final set of experiments confirmed that singleton interference could be found in tasks of visual sequential search, providing a direct visual analogue for the present auditory effects. Overall, this thesis establishes the phenomenon of auditory attentional capture, adding to a growing body of research demonstrating similarities between attentional processes in vision and hearing.

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Chapter 1

General Introduction

1.1 Preface

The brain receives an overwhelming amount of information from all the senses at the same time. In order to respond to this stimulation appropriately, we need to focus our attention on stimuli that are relevant to our current goals, while ignoring stimuli that are currently less relevant. However, although this process of selective attention is essential for coherent behaviour, it is also important that less relevant stimuli can attract attention away from the task at hand if they are likely to signal valuable information about the environment. In particular, a "singleton" stimulus that is unique against a uniform background is likely to indicate an area of the environment that may provide important new information. For example, an orange stimulus among many green stimuli could indicate a fruit among leaves, and it might therefore be useful to direct attention towards this colour singleton even when it is irrelevant to a current task. Similarly, a high pitch sound from a baby that has previously been making lower pitch noises might suggest that the baby requires attention. Once again, although the baby's noises may have been temporarily irrelevant to the task at hand (e.g. listening to someone talking), it is very important to be able to direct auditory attention away from that task and towards the baby when auditory information suggests that the baby's behaviour may have changed.

The process whereby attention is drawn towards "singleton" items that are unique against the background yet irrelevant to an ongoing task has been termed attentional capture (AC). This phenomenon has been the focus of much research, although until recently it has been studied almost exclusively in vision. However, in order to understand attention more fully, we must aim to characterise the ways in which it acts in modalities other than vision. The purpose of this thesis is to examine whether unique yet irrelevant auditory singletons can capture attention away from an auditory task. As hearing is free from the spatial restrictions of the other senses it is often thought of as an early-warning system that can monitor in all directions while vision (the only other sense that can operate at long-range) is focused on a much smaller area of space. As such, hearing can provide us with advance notice of sudden changes in the environment and we might therefore expect auditory attention to be open to capture by singleton sounds, even when they are irrelevant to the task at hand.

This chapter begins with a review of the relevant research into selective auditory attention and interference effects by irrelevant auditory distractors. In the second section I outline the phenomenon of AC as it has been studied within vision and examine the principles of visual AC that are likely to be relevant for AC in the auditory domain. The auditory search task used throughout my experiments was designed in line with these principles, as I discuss in the final section of this chapter.

1.2 Auditory attention

Attentional capture is the process by which singleton items interrupt focused attention despite being irrelevant to the task at hand. In order to ask whether this process occurs within hearing, it is first important to establish that auditory attention can focus selectively on a subset of relevant stimuli at the expense of other stimuli. As I will discuss in the following section, there has been a substantial amount of work showing that auditory attention can be focused in this way. It will then be important to consider previous studies that have asked whether this focused attention can be interrupted by the presence of auditory distractors. I will discuss this research in section 1.2.2.

1.2.1 Selective auditory attention

There is considerable evidence that auditory attention can focus on subsets of task-relevant stimuli if they are separated from task-irrelevant stimuli on the basis of a particular auditory feature (such as frequency or intensity). I will outline results from several different paradigms that converge on the conclusion that auditory attention can be selective in this way.

Dichotic listening

Early studies using the dichotic listening technique found that participants could selectively attend to auditory information presented to one ear (which they were often asked to shadow) while apparently ignoring information presented to the other ear (as indicated by failures to report information presented there, e.g. Cherry, 1953; Moray, 1959). This selective focusing of attention was found to be greatly improved if the relevant and irrelevant messages were distinguished by a simple auditory feature (such as the pitch of the voice speaking the words) as well as by ear of presentation. This observation provided some of the earliest evidence to suggest that auditory attention could focus on stimuli containing a particular auditory feature at the expense of stimuli that did not contain that feature.

Further research found that the attentional selection obtained within the dichotic listening tasks was not completely effective. Even the earliest experiments found that, while semantic changes in the content of the unattended channel typically went unnoticed, changes in the simpler physical characteristics of the unattended stimuli, such as the pitch of the speaking voice, were often detected (Cherry, 1953). Further studies found that words in the unattended channel were sometimes noticed if they contained very salient semantic information such as the subject's name (Moray, 1959) or if they were temporarily primed by virtue of their semantic meaning. For example, subjects sometimes switched from shadowing the attended message to shadowing the message they had been instructed to ignore, if this made semantic sense (e.g. if the phrase "dear, four, Jane" was played to the attended ear and the phrase "three, aunt, five" was played to the unattended ear, subjects were more likely to shadow the phrase "dear aunt Jane" than the phrase "dear four Jane", even though this involved shadowing the word "aunt" from the unattended ear; Gray & Wedderburn, 1960). Overall the dichotic listening studies broadly agreed that auditory attention could selectively focus on sounds containing a particular auditory feature, with only information that was either very basic (e.g. changes in pitch) or semantically primed (e.g. the subject's name) disrupting this attentional focus.

However the dichotic listening tasks typically involved presentation of fairly complex speech information and the strength of attentional focus was therefore measured with techniques such as semantic priming or recognition memory. As such, these studies are subject to semantic processes as well as alternative accounts in terms of memory. This prevents clear interpretation of these findings in terms of the extent to which selective attention reduces perception of irrelevant information. Clearer effects of focused attention on auditory perception have been demonstrated in the studies discussed below, which use simpler auditory stimuli (e.g. pure tones) and assess performance on the basis of detection or discrimination RTs and accuracy.

Expectancy

There is evidence to suggest that subjects are better at processing sounds at an expected frequency or intensity than at an unexpected one. This research has shown that subjects are able to focus auditory attention on a band of attended frequencies or intensities, at the expense of values falling outside the attended range. For example, Greenberg & Larkin (1968) tested subjects' detection of tones presented at levels that were just above threshold. On each trial a tone would be presented in one of two time intervals and subjects were asked to indicate in which of the two intervals the tone had appeared (this is known as a two-interval forced choice task). Greenberg and Larkin found that subjects expecting a frequency of 1100 Hz detected tones with frequencies under 1000 Hz or over 1200 Hz much less often than they detected tones falling within the range of ±100 Hz from the expected frequency. Similar results were found (for different expected frequencies) in two-interval forced choice tasks with tones presented against a background of white noise (e.g. Yama & Robinson, 1982; Scharf et al., 1987).

Expectancy can also be based on the dimension of intensity. For example, Nosofsky (1983) asked subjects to judge on each trial whether the second of two sounds was louder or softer than the first. On some trials, both sounds were of a relatively high intensity, and on other trials both were of lower intensity. Nosofsky found that performance on the discrimination task improved as subjects were given more examples at a particular intensity range. For example, if ten successive trials involved low intensity sounds, performance would be better by the eighth trial at that range than at the beginning. If stimuli then changed to the high intensity range, performance dropped back down (but would improve again if several trials were presented at this intensity range). These results imply that subjects could focus their attention on sounds of a particular intensity, and that it would take several trials at a new intensity range before they were able to shift their attention to focus on that range.

There is also evidence that judgements about a particular dimension of a target sound can be improved if that sound is at an expected value on a different dimension. For example, Mori & Ward (1991) found that subjects' intensity discriminations were more accurate if all tones were of the same frequency, rather than all tones being of different frequencies. Mondor, Zatorre & Terrio (1998) also found that participants responding to the location of tones performed better if those tones did not also vary on the irrelevant dimension of frequency. Similarly, irrelevant variations in location interfered with responses to the frequency of the tones. Luce and Green (1978) asked subjects to discriminate the frequencies of successive tones, responding after each tone according to which of two possible frequencies had been presented. Performance was better if the tones they were judging were at, or close to, an expected rather than an unexpected intensity (see also Green & Luce, 1974).

Cuing

Studies of auditory cuing also provide evidence to support the idea that attention can focus selectively on particular frequencies and intensities. For example, Mondor and Bregman (1994) asked participants to judge the durations of target tones (short vs. long). Responses were faster and more accurate when a sound 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 Howard, O'Toole, Parasuraman, & Bennett, 1984; Scharf et al., 1987; Ward & Mori, 1996; Ward, 1997). This suggests that auditory attention was drawn towards the frequency of the preceding "cue" sound, facilitating performance for successive sounds at that frequency but interfering with performance for a following sound of a different frequency. Similar studies have shown that auditory attention can also be drawn to previously cued intensities and durations. For example, Mondor & Lacey (2001) found that subjects were slower and less accurate in identifying the duration, intensity or timbre of a target sound when a preceding sound differed from the target in duration or intensity (compared with trials in which the target and preceding sound shared the same duration or intensity).

Although this type of cuing towards ranges of frequencies, intensities or durations is typically considered to be exogenous (e.g. Dai & Buus, 1991; Ward, 1997), there is also evidence that attention can be cued endogenously. For example, Hafter, Schlauch and Tang (1993) demonstrated that subjects were able to make use of "relative" frequency cues. Probe sounds (presented against a background of white noise) were detected more accurately when they had frequencies at a certain reliable separation from the frequency of the cue sound (e.g. when probe sounds were at the musical interval of a 5th below the cue sound) than when the cue sound was absent. This suggests that subjects were able to use frequency cues endogenously, voluntarily allocating attention to the frequency region at the correct separation from the cue sound.

Auditory streaming

Another line of evidence that auditory attention can selectively focus on sounds with a particular relevant feature comes from studies of the effects of auditory streaming. This research has demonstrated that a single sequence of sounds can, under certain conditions, be perceived as two different groups (or "streams"; e.g. Bregman and Campbell, 1971). This auditory streaming effect usually occurs when the sounds in the sequence are of high and low frequencies alternately (with frequency separations of at least 4 semitones) and when rates of presentation are high (e.g. Van Noorden, 1975). Under these circumstances, subjects tend to perceive two concurrent streams, one consisting of the high frequency sounds and one of the lower sounds.

There is evidence that attention can focus exclusively on one of these perceptual streams, at the expense of sounds that are perceived as belonging to another stream. For example, Bregman and Campbell (1971) presented subjects with three different high frequency tones (ABC) and three different low frequency tones (123) in a repeating sequence (e.g. A1B2C3A1B2C3... etc) with frequency differences and timings designed to provoke stream segregation. When they were asked to report the order of the tones, subjects tended to respond either "ABC123" or "123ABC", suggesting they had not been able to focus attention on both streams at the same time. It appeared that subjects had attended to the order of items within the two segregated frequency streams rather than across the sequence as a whole (see also Dowling, 1973). Thus, auditory attention appears to be able to focus selectively on particular groups of sounds that are distinguished from other groups simply on the basis of frequency.

There is also limited evidence to suggest that, as is also the case in visual attention (e.g. Baylis & Driver, 1992; Duncan & Humphreys, 1989), factors such as target-nontarget similarity and nontarget-nontarget similarity can strengthen auditory perceptual segregation of attended and unattended groups, increasing efficiency of auditory attentional focus. Leek, Brown & Dorman (1991) presented subjects with sets of three rapid sequences of nine tones, one after another. The first sequence was always the standard and subjects were asked to discriminate between the following two sequences, responding according to which of them was the same as the standard. One of these following sequences would always differ from the standard, in that one sound only (the target) would have a slightly higher frequency than the corresponding sound in the standard sequence. Performance on the discrimination task improved systematically with increased frequency separation between the "target" and "nontarget" tones. Leek et al. (1991) also found that increased intensity separation of the target from the nontargets led to improved frequency discriminations of this type. Thus the degree of target-nontarget similarity plays a role in determining the effectiveness of focused auditory attention. There is also evidence that nontarget-nontarget similarity can affect the efficiency of auditory attentional focusing. Bregman and Rudnicky (1975) asked subjects to make order judgements about a pair of tones of different frequencies, A and B. Although this is an easy task when the tones are presented in isolation, it becomes significantly more difficult if distractor tones (of a third frequency, X) are presented before and after the target tones (e.g. producing the sequence XABX). However Bregman and Rudnicky found that the interference effects of these distractors could be reduced if a series of "captor" tones (of a fourth frequency, C, which was similar to the distractor frequency, X) were presented before and after the distractors (e.g. producing the sequence CCCXABXC). Distractor interference effects decreased with increased similarity of frequency between captor and distractor tones. It is likely that the captor tones reduced distractor interference by streaming with the distractor tones, leaving the target tones in a separate stream and thus making them more easily perceivable. This finding suggests that nontarget-nontarget similarity allows more effective perceptual streaming of stimuli and can therefore contribute to efficient focusing of auditory attention.

Similarly, Alain and Woods (1993) asked subjects to listen to a sequence of sounds and attend to those of a particular frequency (2096 Hz), detecting occasional targets defined by either longer duration or higher intensity. Detection performance was faster and more accurate if the irrelevant nontargets in the sequence were all of similar frequencies (1482 Hz and 1400 Hz) than if the nontargets were of more different frequencies (1482 Hz and 1048 Hz). Thus, as in visual attention, the factors of target-nontarget similarity and nontarget-nontarget similarity can affect the efficiency of auditory selective attention, presumably by allowing stronger streaming into attended and unattended groups.

ERP research

The suggestion that focused auditory attention can affect early perceptual processing of ignored sounds has also received support from event-related potential (ERP) studies. In a typical design, subjects are asked to attend to a sequence of tones defined as having an easily discriminable feature (such as a particular frequency or ear of presentation) while ignoring stimuli that do not have that feature. ERPs elicited by the attended stimulus are then compared with ERPs elicited by the same stimulus when it is unattended. Although there is no physical difference between the stimuli, they typically elicit very different ERPs even at relatively short latencies, suggesting that selective auditory attention can have an important effect even on early perceptual processes. For example, there have been many observations of attentional differences starting at 60 to 80 ms after stimulus presentation (e.g. Hillyard, Hink, Schwent and Picton, 1973; Hansen & Hillyard, 1983; Näätänen, Gaillard & Mäntysalo, 1978) and there is even some evidence to suggest that these differences can occur as early as 20 to 50 ms after stimulus presentation (e.g. Hoormann, Falkenstein & Hohnsbein, 2000).

Neuroimaging research

There have been very few neuroimaging studies of auditory selective attention. However, the limited research in this area agrees that paying attention towards auditory stimulation (compared with ignoring the stimulation) activates areas of primary auditory cortex as well as temporal lobe auditory association areas (e.g. Grady et al., 1997; O'Leary et al., 1997), implying, in line with the ERP research, that selective attention has an effect on auditory perception.

1.2.2 Distractor interference effects on auditory selective attention

The studies reviewed so far have demonstrated that attention can focus selectively on a subset of task-relevant auditory stimuli. The current 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 specific issue has not yet been addressed, there has been some research into the more general issue of interference by auditory distractors.

Behavioural findings

Some of the earliest research into the behavioural effects of auditory distractors concerned the orienting reflex. This is a response that typically involves head and body movements towards a novel auditory event occurring against an otherwise empty background (e.g. Pumphrey, 1950; Sokolov, 1963). The fact that novel, unique auditory events can elicit an orienting reflex is generally encouraging for the present aim of demonstrating auditory AC by unique singleton distractors. However, singleton distractors in the typical AC paradigm are not novel (rather they are presented on 50% of the trials and subjects are aware that they are likely to appear). Research suggests that subjects quickly become habituated to such repeated stimuli, so that these stimuli cease to elicit an orienting response (e.g. Sokolov, 1963). Furthermore, singleton distractors in the present experiment are typically presented against a background of several other stimuli making up a search array, unlike the stimuli used to elicit the orienting reflex, which appear against an empty background. It is therefore not clear whether the singleton distractors used in the typical AC paradigm would elicit an orienting response.

Some more recent studies have found evidence to suggest that auditory distractors can interrupt focused auditory attention, leading to interference in behavioural tasks, even if they do not cause an overt response such as the orienting reflex. Recall that many of the studies of auditory expectancy found that performance in judgement tasks on a particular dimension (e.g. intensity) was better when stimuli did not vary on another dimension (e.g. frequency) than when they did (e.g. Luce & Green, 1978; Mondor, Zatorre & Terrio, 1998; Mori & Ward, 1991). In other words, if a target sound contains a distractor feature (i.e. a feature that causes irrelevant variation on a non-target dimension), this tends to interfere with performance. However, in these studies the irrelevant variation is presented within the target sounds themselves. There is evidence that, at least for certain dimensions (including pitch and loudness), auditory attention cannot be selectively focused on one dimension of a sound while ignoring another dimension of the same sound (e.g. Grau & Kemler Nelson, 1988; Melara & Marks, 1990; Wood, 1975). The phenomenon of AC involves irrelevant singleton features that are presented in a clearly separate nontarget object. The auditory studies described above cannot provide information about subjects' ability to ignore such nontarget sounds.

A few of the auditory streaming studies (discussed in section 1.2.1) have looked at the behavioural effects of distractors that are presented separately from the target. These studies demonstrated that focused auditory attention can be interrupted by irrelevant sounds as long as those sounds are perceived as part of the same stream as the target. Recall, for example, that Bregman and Rudnicky (1975) found that interference from distractor tones could be reduced if they were flanked by "captor" tones allowing perceptual segregation of targets and distractors. However, apart from these few studies there has been very little behavioural research into auditory distraction.

ERP research

There has been extensive ERP research into the effects of sounds that form a change in a repetitive auditory sequence. Although this line of research has rarely addressed the effects of distractor items explicitly, singleton distractors are, by definition, unique against a relatively homogeneous background, and are thus likely to be perceived as causing a change in an ongoing auditory sequence. The ERP research discussed here may thus speak indirectly to the issue of singleton distractor interference.

A typical finding is that deviant sounds (i.e. those that differ from the standard sounds in the sequence on one or more frequency dimensions) tend to elicit an ERP component termed the mismatch negativity (MMN; e.g. Näätänen, 1975, 1979, 1990; Näätänen & Gaillard, 1983; Näätänen, Gaillard & Mäntysalo, 1978, 1980; Näätänen et al., 1989; Sams, Paavilainen, Alho & Näätänen, 1985; Takegata, Paavilainen, Näätänen & Winkler, 1999; for review see Näätänen, 1992). This negativity is not elicited at the beginning of a stimulus sequence (Sams et al., 1985). Neither is it seen when stimuli are presented with inter-stimulus intervals of four seconds or more (Mäntysalo & Näätänen, 1987). It therefore seems genuinely to be a response to a change in ongoing stimulation.

The MMN is generated from supra-temporal brain areas, suggesting that it reflects activity in primary or association auditory cortex (eg. Scherg, Vasjar & Picton, 1989). In line with this possibility, it appears about 100 ms after the onset of the deviant sound, suggesting that it reflects a comparatively low-level change detection process that requires little input from higher-order cognitive processes. Together these findings strongly suggest that the MMN is unlikely to relate to attentional processes but is instead likely to reflect auditory perception of the deviant sound.

However the ERP research has also investigated the question of the attentional responses that may follow elicitation of the MMN. There is evidence to suggest that the MMN is often followed by a component known as P3 (e.g. Näätänen, Simpson & Loveless, 1982; Sams, Paavilainen, Alho & Näätänen, 1985), which is generated at around 300 ms after onset of the stimulus and is known to be associated with attentional orienting towards novel stimuli (e.g. Knight, 1984; Friedman, Cycowicz & Gaeta, 2001). Note that the P3 response to unexpected novel stimuli (referred to as the "novelty P3") is dissociable from the P3 response to target stimuli (referred to as the "target P3") (e.g. Donchin, Spencer & Dien, 1997). In particular, the novelty P3 response becomes habituated over time (e.g. Cycowicz, Friedman & Rothstein, 1996; Debener, Kranczioch, Herrmann & Engel, 2002; Friedman & Simpson, 1994) and is not open to top-down influences such as strategies for allocation of processing resources (Debener et al., 2002). By constrast, the target P3 does not become habituated over time and can be influenced by top-down factors (Debener et al., 2002). This suggests that deviant sounds that elicit a novelty P3 response when presented within the typical MMN task might capture attention in a bottom-up, stimulus-driven manner. However, very few of these studies have measured behavioural responses, and without behavioural measures it is hard to tell whether such attentional orienting would have an effect on performance of a concurrent task.

There have been a few MMN studies that have also assessed behavioural measures of performance. For example, Schröger and Wolff (1998a) demonstrated that performance on a duration judgement task was worse if the sound being judged was of low-probability "deviant" frequency, than if it was of standard frequency. They presented subjects with a series of sounds, of which 50% were long (200 ms) and 50% were short (100ms). Subjects were asked to make a button press whenever they heard a long sound. Sounds also varied in frequency, being either standard (90% of sounds) or deviant (10%). Reaction times were longer and responses less accurate when the targets were of deviant frequency than when they were of standard frequency. The ERP recordings from this study indicated that deviant stimuli elicited the MMN as well as a P3a response, implying that the behavioural distraction observed may have been due to attentional orienting towards the deviant feature. However, as this deviant feature was in fact presented within the target sound itself, the deviance was not truly irrelevant to the task. As such, this study cannot provide information about the effects of an irrelevant singleton feature that is presented in a nontarget object (similarly to Mori & Ward, 1991, and Mondor, Zattore & Terrio, 1998).

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. The deviants in this study elicited reliable MMNs, and there was also some evidence to suggest that they were followed by P3a responses (however precise measurements were made difficult by the presence of a second stimulus appearing very soon after the first).

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. In other words it is not clear whether the deviant sounds really captured attention or whether attention was allocated to all the preceding sounds in the irrelevant ear because of their ability to cue the target. In the latter case, the interference by the deviant sounds could be explained in terms of the attentional cuing effects described earlier (e.g. Mondor & Bregman, 1994), as it is likely that attention would focus on the frequency of each preceding sound, producing a cost when this frequency did not match that of the subsequent target. In order to establish that attention is unintentionally captured by an irrelevant singleton sound it is important to ensure that it does not predict the target sound.

Finally, the deviants used in Schröger and Wolff (1998a) and Schröger (1996) did not have to compete for attentional resources. Presentation rates were very slow (typical ISIs were in the range of 1 second, e.g. Schröger & Wolff, 1998a) so that subjects would have time to pay attention to each stimulus in turn. Thus neither of these studies can provide information about whether responses to stimuli that that are irrelevant to the task at hand and must compete for attention with other stimuli under speeded presentation can nevertheless capture attention.

A few studies have found evidence to suggest that if the deviant sound eliciting the MMN (and P3a) is "irrelevant" to an ongoing task, the P3a is followed by a frontal negativity known as the reorienting negativity as it appears to reflect a process of reorienting of attention towards task-relevant stimuli (e.g. Schröger, Giard & Wolff, 2000; Schröger & Wolff, 1998b). However, although this finding indirectly implies that attention was oriented towards the deviant sound (and then had to be re-oriented towards the target), the same criticisms apply here as mentioned in relation to the previous two studies: the tasks were relatively undemanding and the deviants were not truly irrelevant, thus it is not surprising that attention was oriented towards them.

Finally, some studies have addressed the more general question of whether attentional processes might be involved in elicitation of (or response to) the MMN. There is evidence that the MMN is elicited normally when subjects are reading a book (Sams, Paavilainen, Alho & Näätänen, 1985), carrying out demanding problems (Duncan & Kaye, 1987; Lyytinen, Blomberg & Näätänen, 1992) and even when they are sleeping (e.g. Campbell, Bell & Bastien, 1991). This suggests that attention may not be necessary for elicitation of the MMN. However note that the concurrent tasks in these examples do not make any demands on auditory attention, and it is therefore likely that there are sufficient resources left over to process auditory deviants.

In fact, there is evidence that the MMN can be reduced or even eliminated in situations where the deviant sounds are in competition for auditory attention (i.e. they are competing with other auditory stimuli rather than with a task in a different modality). For example, Woldorff, Hackley & Hillyard (1991) asked subjects to carry out a dichotic listening task in which attended and unattended streams were differentiated both by ear of presentation and by pitch. The task was to attend to a particular stream of rapidly presented stimuli (with ISIs ranging from 120 ms to 320 ms) and detect occasional targets that deviated very slightly in intensity from the other sounds in the stream. The difficulty of the task was titrated for each subject by varying the intensity difference between targets and nontargets until a detection rate of 70-80% was achieved. Woldorff et al. (1991) found that intensity deviants in the unattended ear led to significantly reduced MMNs compared with deviants in the attended ear, and compared with previous measurements of MMNs to similarly sized intensity differences. In a second experiment, when the stimuli were presented at even faster rates (with ISIs ranging from 65 ms to 205 ms) the MMN was barely present at all. Thus it seems that if a demanding task causes auditory attention to be focused strongly enough on a particular set of stimuli, irrelevant changes in another set can be ignored to such an extent that the MMN which would normally accompany such changes is reduced or even eliminated (see also Woldorff et al., 1998).

Moreover, Trejo, Ryan-Jones & Kramer (1995) showed that irrelevant deviants could be ignored even without a dichotic listening design. They presented subjects with a narrative interspersed with tones. Tones could either be of standard frequency (occurring 80% of the time) or of one of two deviant frequencies (each appearing 10% of the time). Subjects were asked either to attend to the narrative (listening for target words) or to attend to the tones (listening for a particular frequency deviant). When subjects were attending to the narrative, the MMN to the interspersed deviant tones was reduced compared to the MMN obtained for the same tones when subjects were attending to them. Again, this finding suggests that focused auditory attention can reduce the MMN to unattended deviants. It is important to note that this result did not rely on the highly-focused dichotic set-up used by Woldorff et al., but instead was found in a sequential design where unattended and attended stimuli were interspersed in a single sound sequence. Thus relevant and irrelevant auditory stimuli do not need to be separated in space in order for subjects to be able to ignore the irrelevant ones.

Overall, it seems that the simple detection of a deviant item (as indexed by the MMN) can be sufficient to draw attention towards that item (as indexed by the P3a component), as long as there are no other demands on auditory attention. However, in situations where there is competition for auditory attention, the MMN to irrelevant deviants can be significantly reduced or eliminated. These findings imply that such deviants capture attention and indeed depend on attention for their processing. However, due to differences in the nature of the stimuli (e.g. the irrelevant singletons used in AC tasks typically occur on 50% of trials and are therefore less rare than the deviants used to elicit the MMN) and in the tasks used (e.g. the singletons used in AC tasks are typically defined on a task-irrelevant dimension and do not predict the target in any way), these studies are inconclusive regarding the question of whether an irrelevant singleton that is not very rare can capture attention.

1.2.3 Summary

The research described above has shown that auditory attention can focus on a subset of stimuli defined as having a particular relevant feature, at the expense of stimuli that do not have that feature. The efficiency of this auditory attentional focus depends on the extent to which auditory stimuli can be organised by the perceptual system into clearly differentiated attended and unattended groups. There is some suggestion that auditory distractors can interfere with focused auditory attention, but the effects of singleton distractors that are irrelevant to the task at hand have not been studied.

1.3 Attentional capture in vision

Attentional capture has been studied in vision using two main paradigms. The first uses the spatial cuing paradigm to assess the extent to which singleton items can capture attention, producing spatial cuing when presented as pre-cues before a search display. The second examines whether singletons presented during tasks of visual search can capture attention, interfering with responses to the target. The present review describes the results from each paradigm in turn. However, as the aim of this thesis is to examine whether auditory singletons presented within an auditory search array can produce attentional capture, the present review highlights in particular the findings from the visual search paradigm.

1.3.1 Attentional capture within spatial cuing tasks

In a typical spatial cuing task, a cue is flashed on screen, followed by a target display in which subjects must either detect the presence (vs. absence) of a particular target or discriminate between two possible targets (e.g. one letter or another). If the cue is valid (i.e. presented in the same location as the subsequent target) target performance (measured by reaction times and/or accuracy) is better than if the cue is invalid (i.e. presented in another location, e.g. Jonides, 1981; Müller & Rabbitt, 1989). Jonides (1981) showed that cuing effects are more difficult to suppress if the cue appears in the periphery of the display, adjacent to the subsequent target position than if the cue appears in the centre of the screen, indicating subsequent target position by the direction in which it is pointing. Indeed, subsequent research has shown that peripheral cues can interfere with search even when they are made 100% invalid, i.e. when they never indicate the position of the target (Remington, Johnston & Yantis, 1992). Thus it seems that peripheral cues "capture" attention in an involuntary way that cannot be overridden by prior knowledge of cue invalidity.

Spence and Driver (1997) found similar results. They asked participants to judge the elevation (high vs. low) of visual targets presented on the left or right hand side of the subject. Responses were faster and more accurate when targets were preceded by visual cues on the same rather than the opposite side, suggesting that these cues had captured attention despite being valid on only 50% of trials. Interestingly, Spence and Driver (1994, 1997) also showed that auditory cues could affect performance of an auditory elevation discrimination task in the same way (see also McDonald & Ward, 1999; Mondor, Breau & Milliken, 1998; Mondor & Zatorre, 1995; Quinlan & Bailey, 1995; Schröger & Eimer, 1997). This provides a demonstration of auditory AC within a spatial cuing design.

However the objects (cues) that capture attention in both the visual and auditory spatial cuing tasks discussed so far have typically been presented on their own against an empty background. As such, attention would have been very likely to be drawn towards the cues, as there were no competing items to attract attention. Thus these studies do not provide information about AC by a singleton stimulus that is in competition for attention with other stimuli. This issue has been addressed most thoroughly within the demonstrations of AC that have used a visual search design, as I will discuss in section 1.3.2.

However, several studies have used a modification of the spatial cuing design that allows them to assess the spatial cuing effects of a singleton stimulus presented among other items in a pre-cue display. A typical finding is that AC due to these singleton cues is not involuntary (as in the studies of isolated peripheral cues, e.g. Remington et al., 1992) but instead is subject to influence by factors such as attentional set. For example, Folk, Remington and Johnston (1992) presented subjects with a pre-cue display followed by a visual search task. However, in contrast with the studies discussed above, the pre-cue display contained several items, so the cue was presented in competition with other items rather than appearing against an empty background. One of the items in the pre-cue display was unique, either on the dimension of abrupt-onset (i.e. appearing in a previously unmasked location while all the other items appeared in masked locations) or on the dimension of colour (e.g. red among green). As in previous spatial cuing studies, Folk et al. (1992) measured AC in terms of cuing effects, such that if a singleton captured attention it would produce a cost (compared with a no distractor condition) when presented in an invalid location and a benefit when presented in a valid location. They found that invalid precue singletons that were unique on the dimension of abrupt-onset captured spatial attention in this way, but only if the target of the subsequent search task was also defined by abrupt-onset. When the target was defined on the dimension of colour, the invalid abrupt-onset singleton did not capture attention. Broadly the same pattern of results was found for invalid precue singletons defined by colour: they appeared to capture attention if the subsequent target was also defined by colour (even if it was of a different colour to the singletons) but not if it was defined by onset. This implies that a singleton pre-cue presented among other competing items will only capture spatial attention if the subject's attentional set includes the dimension on which the singleton is defined. Note however that Folk et al. (1992) made a distinction between static discontinuities (e.g. caused by colour or shape singletons) and dynamic discontinuities (e.g. caused by abrupt-onset or motion singletons). They did not claim that a subject's attentional set could distinguish between two static discontinuities (e.g. focusing on colour while ignoring shape) or two dynamic discontinuities (e.g. attending to motion while ignoring onset), but only that it could differentiate between the wider categories of static versus dynamic discontinuities in general (e.g. focusing on colour while ignoring onset; see also Folk, Remington & Wright, 1994).

Folk & Remington (1998) ran an experiment based on the study of Folk et al. (1992) but with the difference that they presented both valid and invalid precue singletons within the same block (Folk et al., 1992, had presented valid and invalid singletons in separate blocks). The invalid singleton was completely uncorrelated with subsequent target position (i.e. it appeared in the same position as the subsequent target on 1/n of the trials, where n is the number of elements in the array), thus there should have been no incentive to attend to the singleton. Nevertheless, Folk and Remington found that subjects searching for a colour singleton target were distracted by the appearance of an irrelevant colour singleton in the pre-cue array. However this irrelevant singleton only captured spatial attention (as indicated by cuing effects depending on whether the singleton and subsequent target were in the same or different locations) when it was defined by the same feature value as the target (e.g. when both were red among a homogeneous array of white items). When the defining features were different (e.g. the target was red, and the singleton was green) the presence (vs. absence) of the singleton produced a general cost to search performance that was not location-specific. Thus it seems that there may be more than one type of AC: a spatial effect that appears to depend at least to some extent on the observer's attentional set (see also Atchley, Kramer & Hillstrom, 2000); and a cost that is not location specific and does not depend on attentional set, and that is driven by bottom-up factors such as the salience of the items in the array.

Interestingly, there is evidence to suggest that subjects carrying out spatial cuing tasks can adopt an attentional set based on features that indicate the presence of the whole search array, rather than just the target feature. For example, Gibson and Kelsey (1998) found that search for a letter of a particular identity among other letters was disrupted by the presence of an irrelevant singleton presented in a precue display, as long as the singleton contained one of the features that signalled the appearance of the search display. For example, when the letter search array consisted of red letters and appeared with abrupt-onset, both red singletons and abrupt-onset singletons captured attention. On the other hand, when the letter search array consisted of white letters (so that subjects would be unlikely to adopt an attentional setting for colour) only abrupt-onset singletons captured attention. However note that attentional settings for display-wide features may be less precise than settings used to identify particular targets. For example, Johnson, Hutchinson & Neill (2001) demonstrated that colour singletons in the precue array captured attention even when they did not share the same colour as the subsequent target array (e.g. when the irrelevant distractor was green and the subsequent search array was red). Interestingly, Johnson et al. (2001) found that such singletons did not capture attention if they were presented within the target array itself. Thus the results of this type of spatial cuing study are likely to be different from the visual search results described in the following section.

1.3.2 Attentional capture within visual search tasks

The issue of AC by a singleton stimulus that is presented among other, competing stimuli has also been addressed within the paradigm of visual search. Indeed the majority of visual AC studies have used a visual search design. In a typical experiment, subjects are asked to search visual arrays for a target item defined on a particular dimension (e.g. shape). On a certain percentage of trials, one of the nontargets is unique on a dimension that is irrelevant to the task (e.g. colour). This unique yet irrelevant item is referred to as the "irrelevant feature singleton" or simply the "singleton". A common finding is that the presence of the singleton in the search array interferes with visual search performance, even though it is unique on a dimension that is never relevant to the task. This interference is explained in terms of AC by the irrelevant singleton.

In the following review I will describe the typical findings from the visual search AC studies and highlight the important characteristics of AC as it occurs within this paradigm. Note that, whereas some of the visual findings provide information about general properties of AC that are not modality-specific and may therefore apply to auditory AC (e.g. top-down factors), other findings seem more likely to be modality-specific (e.g. the particular visual features used for target and singleton definition). My review will emphasise those characteristics of visual AC that are unlikely to be modality-specific.

Basic findings

The phenomenon of AC in visual search was originally demonstrated in two influential studies by Jonides and Yantis (Jonides & Yantis, 1988; Yantis & Jonides, 1984). Jonides and Yantis (1988) asked subjects to search arrays of letters for a target letter (pre-specified at the beginning of each trial) that was present on 50% of the trials. This type of letter search is demanding and tends to be carried out in serial (as indicated by reaction times that increase with the number of items in the search array). On every trial, one letter, the singleton, differed from the others by virtue of its abrupt onset (i.e. the singleton appeared at a position that was previously empty whereas the other items were preceded by masks, parts of which were later removed to reveal the items themselves). This abrupt-onset singleton was uncorrelated with target position (i.e. on target-present trials, the target itself was just as likely to appear with abrupt-onset as the other letters), thus there should have been no incentive for subjects to attend to the onset item. Nevertheless, search was found to be highly efficient (as indicated by reaction times independent of the number of items in the search array) when the target letter appeared with abrupt-onset. This suggests that the singleton feature had captured attention, despite being uncorrelated with target position. Interestingly, neither colour nor luminance singletons captured attention strongly enough in this study to produce efficient search when they coincided with the target (see also Gibson & Jiang, 1998; Todd & Kramer, 1994). I will return to the issue of whether abrupt-onset singletons are more capturing than other types of singleton later in this section (in the sub-section on stimulus characteristics).

In contrast to the findings of Jonides & Yantis (1988) there have been several clear demonstrations of AC in different visual search tasks by singletons with features that do not involve abrupt-onset. For example, Pashler (1988) asked subjects to search arrays for a target of unique form (either a circle amongst tilted lines or a tilted line amongst circles). On half the trials the form of the target was specified in advance, while on the other half of trials the target form remained unspecified. Random variation in the colour of the display elements did not interfere with search (Experiments 1, 2 and 4). However, when the colour variation involved the presence of two colour singletons, search for a target of unspecified form was significantly disrupted (Experiment 6). As search for the target was based on form, the result shows AC by colour singletons despite their irrelevance to the task at hand. Interestingly, search for a target whose form had been pre-specified was not affected. This appears to suggest that AC is not completely involuntary but rather depends at least to some extent on the specific demands of the task (I will discuss this possibility further in the sub-section on top-down factors).

However, Theeuwes (1991a, 1992) found evidence that colour singletons can capture attention even when the target form is pre-specified. Using only one singleton presented at a smaller eccentricity (and therefore with higher retinal acuity) than those used by Pashler (1988), he showed that reaction times in search for a pre-specified form target (a circle among diamonds) were increased whenever one of the nontarget diamonds differed in colour from the rest of the items in the display (see also Turatto &

Galfano, 2001, for a similar demonstration of AC by colour singletons in a task where subjects searched for a pre-specified target: a rotated letter T among rotated letter Ls).

The influential studies discussed above have established visual AC by irrelevant singleton distractors defined by both abrupt-onset and colour. Below I discuss several aspects of the visual AC findings in more detail.

Facilitation

In most studies of visual AC, the irrelevant singleton feature is presented within a distractor item and AC is measured in terms of interference with search, as attention should be drawn away from the target towards the irrelevant singleton items (e.g. Theeuwes, 1991a, 1992). However, if this interference reflects genuine AC by the irrelevant singleton feature, then search should be facilitated when this singleton feature coincides with the target item, as attention should then be drawn towards the relevant target object. Recall that the studies of Yantis and his colleagues (e.g. Jonides & Yantis, 1988; Yantis & Jonides, 1984) relied on observations of facilitation for their demonstrations of AC (i.e. they showed that search for a letter target was efficient if the target item was presented with the irrelevant singleton feature of abrupt-onset but inefficient if one of the distractors had the singleton feature). Indeed, any AC account of interference due to the presence of a singleton feature presented in a distractor object must also predict facilitation by a singleton feature presented in a target object. This logic applies equally to the auditory domain.

Stimulus characteristics

a) Abrupt-onset

Recall that Jonides and Yantis (1988) found AC by abrupt-onset singletons but not by colour or intensity singletons. This finding suggested that singletons defined by abrupt-onset might capture attention under circumstances where other types of singleton did not (see also Yantis and Jonides, 1984, 1990). In particular, Yantis and his colleagues have argued that abrupt-onsets are likely to signal new perceptual objects (e.g. Yantis & Jonides, 1996) and that this may be the reason that they capture attention so effectively. An alternative possibility is that onsets are particularly capturing because they involve abrupt changes in luminance. However, several experiments have controlled for luminance changes and found that abrupt-onsets capture attention nevertheless (e.g. Enns et al., 2001; Gellatly, Cole & Blurton, 1999; Yantis & Hillstrom, 1994).

There has also been considerable debate over whether the abrupt-onset results can be explained in terms of forward masking of the non-onset stimuli, rather than in terms of the strength of AC by abrupt-onsets (e.g. Gellatly, Cole & Blurton, 1999; Gibson, 1996a; 1996b; Yantis & Jonides, 1996). However abrupt-offset has also been found to capture attention very effectively (e.g. Theeuwes, 1991b; Chastain & Cheal, 1999), a result that cannot be explained in terms of masking. In fact, the overall display change involved when the mask display is removed to reveal the search array, may matter more than whether the change involved an onset or offset. For example, Miller (1989) showed that onset targets were only identified efficiently in visual search when the visual change due to the onset item (i.e. addition of several line segments) exceeded the visual change due to the unmasking of the rest of the search items (i.e. removal of segments, see also Martin-Emerson & Kramer, 1997). Thus attention seems to be drawn to the region where the most segments have been removed or added, suggesting that dynamic discontinuities in general are particularly good at capturing attention, with the strength of capture determined by the level of change involved.

The apparent strength of visual AC by dynamic discontinuities is perhaps not surprising from an evolutionary perspective. An abrupt-onset or -offset singleton is likely to signal the appearance or disappearance of a new perceptual object (see Yantis & Jonides, 1996) to which attention should be directed as a matter of priority. It seems plausible that these sorts of dynamic changes might demand more instant attention than static discontinuities (such as colour singletons), and might therefore capture attention more strongly.

However, the specific issue of the importance of dynamic versus static discontinuities in visual AC is not likely to be especially relevant for auditory AC. Whereas abrupt onsets and offsets in vision will almost always occur because of some sudden change in the environment, dynamic discontinuities in hearing are far more common and do not necessarily signal such vital information. For example, a sequence of speech involves countless sounds that appear with abrupt-onset and -offset, yet none of them signals a sudden environmental change. Thus abrupt onsets in auditory stimulation are much less likely to indicate new perceptual objects than abrupt onsets in visual stimulation and the role of abrupt onset (or offset) in auditory AC is therefore likely to be less interesting than it has been in visual AC. Instead, it is possible that a different singleton dimension may prove to be especially good at capturing auditory attention. For example, intensity is likely to be very important within hearing, as the loudness of a sound can provide information about how near a stimulus is and how quickly it is approaching. Thus it is possible that intensity singletons will be especially good at capturing auditory attention.

b) Salience

Another factor that has been found to affect AC is the relative salience of targets and singletons. Theeuwes (1992) found that search for a form target was disrupted by the presence of a colour singleton, whereas search for a colour target was not affected by the presence of a form singleton, presumably because the form singleton used was less distinct among the nontargets than the colour singleton. Indeed, when form singletons were made more salient than colour singletons (by using small differences between target and nontarget colour and large differences between target and nontarget form), form singletons captured attention whereas colour singletons did not (Theeuwes, 1992, Experiment 2).

These findings led Theeuwes (e.g. 1992, 1994a) to propose that AC was a stimulus-driven process, determined entirely by the relative salience of the target and the irrelevant singleton (as long as the target itself was also a feature singleton). Thus it is possible that the relative salience of auditory targets and singletons may influence auditory AC.

Top-down factors

The fact that a nontarget singleton can interfere with search despite its defining feature being irrelevant to the task may at first appear to suggest that visual AC is an automatic, involuntary process. However there is evidence that AC in visual search tasks may depend, at least to some extent on top-down control.

a) Pre-specified target location

One of the first suggestions that visual AC might not be completely involuntary came from Yantis & Jonides (1990). They found that AC by abrupt-onset singletons was eliminated if target position was validly cued (on all trials) so that there was no uncertainty over subsequent target location. Theeuwes (1991b) also found that pre-cuing the location of the target in advance (again using 100% valid cues) attenuated AC by both onset and offset distractors. However, if the location of the target is known in advance, it is unlikely that subjects will carry out any sort of a search process, and it is therefore perhaps not surprising that singleton items do not produce any cost to "search" performance.

Interestingly though, there is evidence that AC can occur under some circumstances even when the search task involves no spatial uncertainty. Folk, Leber and Egeth (2002) presented subjects with rapid serial visual presentation (RSVP) streams and asked them to report the identity of a target letter defined by colour. As array items were presented one after another in the same central location there should have been no uncertainty over the target's spatial location. Nevertheless, Folk et al. (2002) found AC (as indicated by reduced accuracy in the target identification task) due to the presence irrelevant colour singletons that were presented in the periphery of the display (see also Egeth et al., 2001). Thus, although conditions of spatial uncertainty appear to increase the likelihood that AC by irrelevant singletons will occur, AC can still occur when the spatial location of the target is known. This is a particularly interesting finding, as two follow-up experiments showed, using priming techniques, that attention had been drawn towards the spatial location of the distractor. Thus the effect was one of spatial AC and it is therefore especially surprising that it was found even when there was no uncertainty about target location. These results appear to contradict the finding that AC is eliminated if the target location is pre-specified (Theeuwes, 1991b; Yantis & Jonides, 1990). However, as mentioned earlier, the tasks in both these experiments involved a spatial search for the target and spatial certainty over the target location would have removed the need for any search process at all. The crucial difference in Folk et al.'s (2002) study was that, although the spatial location of the target was known in advance, the temporal location remained uncertain and the need for search was thus not removed altogether. Instead, subjects were required to conduct a temporal search for the target, despite being certain of its spatial location.

b) Attentional set

Recall that there is considerable evidence from the spatial cuing research to suggest that singletons presented in pre-cue arrays capture spatial attention only if subjects adopt an appropriate attentional set (e.g. Atchley et al., 2000; Folk & Remington, 1998; Folk et al., 1992; Folk et al., 1994). However, it seems that AC within the visual search design is less open to influence by attentional set. For example, Theeuwes (1994b) found, using a visual search design, that onset and colour singletons both interfered in search for onset targets as well as in search for colour targets. In other words, an attentional set for onset or colour did not prevent AC by singletons that did not also fall within the attended set. Indeed Theeuwes & Burger (1998) showed that AC by colour singletons in search for a colour target is only eliminated if both the distractor and target colours are known in advance. Thus AC can only be prevented if subjects adopt an attentional set for a specific target colour as well as preparing to ignore a specific singleton colour. These results suggest that AC in the visual search design is less open to influence by attentional set than AC in the spatial cuing design.

The difference between the results of the visual search and spatial cuing paradigms might be explained by the finding that there appear to be two distinct types of AC: a more spatial effect that depends on the subject's attentional set; and a non-spatial effect that is less open to the influences of attentional set (Folk & Remington, 1998). In most spatial cuing studies a singleton pre-cue is always present and AC is measured in terms of location effects due to this cue (i.e. AC by the cue leads to facilitation if that cue shares the same location as the subsequent target and interference if the two have different locations). By contrast, in the visual search paradigm effects are compared between singleton present and singleton absent conditions. It is thus likely that the presence (vs. absence) of a singleton (as in the visual search experiments) produces stronger effects than variations in singleton position (as in the spatial cuing experiments), and that these stronger effects are less dependent on attentional set.

c) Search strategy

However AC in visual search does depend on the search strategy available. Recall that the task used by Jonides and Yantis (1988), in which they found no AC by colour or intensity singletons, involved a demanding search for a particular letter among other letters. By contrast, Pashler (1988) and Theeuwes (1992) used much simpler search tasks (for unique "odd-one-out" targets) in their studies demonstrating interference by colour and form singletons. This suggests that the target itself must be a feature singleton in order for a non-onset singleton to capture attention. Indeed Bacon and Egeth (1994) showed that the singleton interference found in Theeuwes (1992) could be eliminated if the target was prevented from being a reliable form singleton (either by presenting more than one target in each array, or by including nontargets of several different forms). Thus it seems that the subject must be looking for a feature singleton target in order for AC by irrelevant singletons to take place. Subjects searching for singleton targets are likely to adopt what Bacon and Egeth (1994) have termed a 'singleton detection mode' in which they scan the search array for any singleton item, and it seems that this search strategy will allow AC to occur whereas a more restricted search for the particular target feature (referred to as 'feature search mode') will not. This would also explain the finding that AC can sometimes be prevented when the target is pre-specified (e.g. Pashler, 1988), as subjects looking for pre-specified targets are more likely to adopt a feature search mode than a singleton detection mode.

1.3.3 Summary

The research described in this section has demonstrated that a visual singleton can capture attention in both spatial cuing and visual search tasks, even when it is defined on a dimension that is completely irrelevant to the task. This visual AC leads to interference if the singleton item is a nontarget in a visual search display (or an invalid precue), but should also be able to facilitate performance if the target of a visual search itself contains the irrelevant singleton feature (or if the singleton is a valid pre-cue).

Visual AC depends on a number of factors, including bottom-up factors such as the relative salience of target and singleton stimuli as well as more top-down influences such as search strategy. It will be interesting to ask whether similar factors are also involved in mediating auditory AC.

1.4 General Method

The tasks used in the present study were designed in line with the findings of the visual and auditory research discussed above. An auditory search task was used, 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 (Chapter 2) or discriminate its feature value (e.g. high frequency or low frequency, Chapters 3, 4 and 5). As I have discussed, previous 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 have been able to focus on sounds containing the relevant target feature at the expense of sounds that did not contain that feature.

The question of current interest was whether the presence of a nontarget with a unique singleton feature would disrupt such focused attention. To examine this, an irrelevant singleton sound (e.g. with higher intensity than the other sounds) was presented on half the trials and target RTs were compared in the presence versus the absence of this singleton distractor.

Participants were presented with rapid serial auditory presentation (RSAP) search arrays, in contrast to the spatial arrays typically used in the visual search experiments (with the exception of Egeth et al., 2001, and Folk et al., 2002). Sequential arrays were used for three reasons: First, most previous research into focused auditory attention and the effects of auditory distractors has used temporal rather than spatial search arrays. Second, there is 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 organised, 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 et al., 2001). A third, 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.

As mentioned earlier, although there has been limited research into the effects of auditory distractors on focused auditory attention, these studies have not looked at the effects of singleton features that are made irrelevant to the task. My aim in the present experiments was to examine the effects of singletons that were genuinely irrelevant, and for this reason singletons in the present experiments (with the exception of Experiment 9) never occurred in the same temporal position as the target (c.f. Schröger, 1996). Any finding of a cost associated with singleton presence is therefore likely to indicate AC by the irrelevant singletons, as there should have been no incentive for subjects to attend to the singleton sounds.

Stimuli were presented very rapidly (with ISIs of 50 ms) so that they would have to compete for attention. The sequences were also designed to minimise any effects of auditory perceptual grouping. Although such auditory streaming can improve efficiency of attentional focus (as discussed in section 1.2.1) it was beyond the scope of this thesis to examine the possible effects of auditory streaming on AC by irrelevant singletons. For this reason, sequences were kept short (containing between four and seven sounds), and frequency and intensity separations of targets, nontargets and singletons were all kept below the thresholds where perceptual segregation effects have been shown to occur (see Van Noorden, 1975).

If irrelevant auditory singletons capture attention in the auditory search tasks described, target RTs should be slower in the presence (vs. absence) of these singletons. Chapters 2 and 3 address this question. Chapter 4 then assesses whether irrelevant singletons can produce facilitation, as well as whether interference due to AC can persist when the singleton does not appear directly before or after the target sound. Chapter 5 asks whether, like visual AC, auditory AC depends on search strategy. Finally, Chapter 6 examines whether AC can be found within a direct visual analogue of the auditory tasks used in this thesis.

Chapter 2

Effects of irrelevant auditory singletons on target detection during auditory search

2.1 Introduction

In this chapter I ask whether an irrelevant auditory singleton can capture attention in a task of auditory search. As in most visual search tasks (including many of the tasks used to examine visual AC), subjects in the present experiments searched for a pre-specified feature target (e.g. with higher intensity than the other sounds) and responded according to whether the target was present or absent. An irrelevant singleton distractor (defined on a different dimension, e.g. with higher frequency than the other sounds) appeared on half of the trials. If this type of singleton captures attention despite being irrelevant to the task, then detection of the auditory target should be worse in the presence (vs. absence) of the singleton distractor.

2.2 Experiment 1

In Experiment 1, subjects were asked to search a sequence of four sounds for a target sound defined as being of higher intensity than the nontargets for half of the subjects, and of lower intensity than the nontargets for the other half of the subjects. Their task was to indicate whether the target was present in the sequence or absent from it. On half of the trials, one of the nontarget sounds was presented at a higher frequency than the other sounds. If auditory attention, like visual attention, has a tendency to prioritise processing of an odd-one-out stimulus that has a unique feature (even when that feature is on a dimension never relevant to the current task) then irrelevant high frequency singletons should capture attention, leading to a cost in task performance (e.g. slower RTs) on singleton present trials compared with singleton absent trials.

2.2.1 Method

Subjects Sixteen paid subjects took part in the experiment. The subjects in all of the experiments reported here were under 35 years old and they all reported normal hearing and normal or corrected-to-normal vision.

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

High intensity stimuli (targets for half the subjects, nontargets for the other half) were presented at an intensity of approximately 83 dB SPL. Low intensity stimuli (nontargets for half the subjects, targets for the other half) were presented at approximately 72 dB SPL. The reported stimulus intensities throughout this thesis were measured using a sound pressure level meter in conjunction with an artificial ear at the subjects' ear position. The target and nontargets had frequencies of 440 Hz. The high frequency singleton sound had a frequency of 520 Hz. Frequencies and intensities were chosen to be easily discriminable, both on the basis of previous research (e.g. Scharf et al., 1987) and as verified by pilot testing.[1]

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[1] 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.

Design and procedure The start of each trial was signalled by a visual display showing the word "ready" for 500 ms. This was followed by a stream of four successive tones, each presented for 100 ms over headphones. The tones 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. Upon presentation of this question mark, 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 on the numerical keypad of the computer keyboard. Participants were restricted to responding at the end of each sequence to ensure that sequences were heard in full before response. Visual feedback was provided at the end of each trial, either after a response had been collected or after 3s 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 next trial began.

Participants were instructed to focus on the target intensity and ignore any sounds of the irrelevant intensity. They were informed that there might be some odd sounds presented at the irrelevant intensity 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 conditions 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. When the target and/or singleton distractor were present, they could occur in 2nd, 3rd or 4th position with equal likelihood. Within each of the four conditions of target and singleton presence, each of the combinations of target and/or singleton position was equally likely.

Three practice blocks of 24 trials 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.

The total run-time for this and subsequent experiments (with the exception of Experiments 13 and 14) was 40-50 minutes.

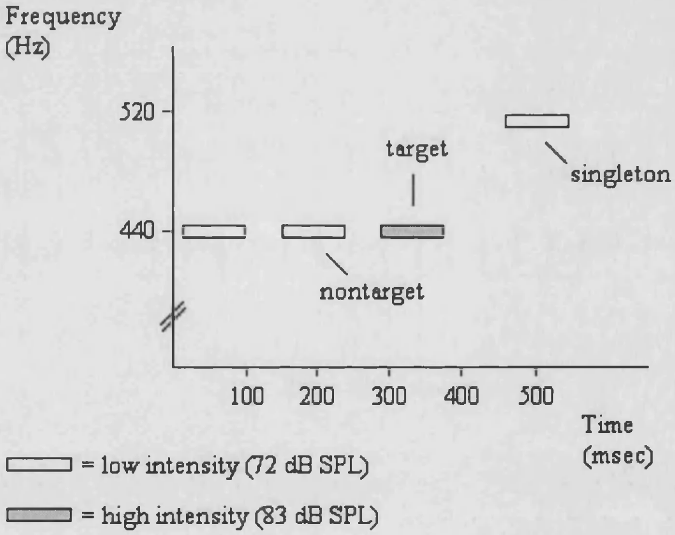

Figure 1: *schematic representation of an example trial from Experiment 1.*
The figure shows an example of a trial where both singleton and target are present. This type of trial made up 25% of the total trials, as described in the method (section 2.1.1). In this example the target is high intensity among low, however half of the subjects received a low intensity target among high.

2.2.2 Results and Discussion

RTs RTs were measured from presentation of the question mark at the end of each sequence. Table 1 presents mean RTs and error rates across subjects as a function of singleton presence (vs. absence), target presence (vs. absence) and target type (high vs. low intensity). 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 thesis.

A three-way mixed model ANOVA with the within-subjects factors of singleton presence (vs. absence) and target presence (vs. absence) and the between-subjects factor of target type (high vs. low intensity) revealed a significant effect of singleton presence [F(1,14) = 23.21, *MSE* = 19760.98, p < .01]. As shown in Table 1, target RTs were slower when the singleton was present (*M* = 309 ms) than when it was absent (*M* = 274 ms). This finding suggests that the singleton distractor captured attention despite being irrelevant to the task. There was also a significant main effect of target presence [F(1,14) = 4.70, *MSE* = 4561.15, p < .05] such that detection RTs were slower in the absence (*M* = 300 ms) versus presence of the target (*M* = 283 ms). Such slowing is in line with previous findings of slowed RTs in visual search for target absent trials compared with target present trials, and may be attributed either to a slower decision or to greater scanning of stimuli in the target absent case. Notice also that, due to the sequential presentation used, subjects could start preparing responses to target present trials somewhat earlier than responses to target absent trials. There was no main effect of target type [F(1,14) = 1.31, *MSE* = 32927.28, p = .271].

There was a significant interaction between singleton presence and target presence [F(1,14) = 7.45, *MSE* = 4224.19, p < .05] indicating a greater cost when the target was absent (mean interference effect = 52 ms) versus present (mean effect = 19 ms). The finding that AC by the singleton distractor was not as strong when the target was also present may have been due to the singleton having to compete for attention with the target when both target and singleton were present. Note however that the simple main effect of singleton presence was significant even on target present trials [t(15) = 3.26, p < .01].

Table 1
Averages of subjects' mean RTs in ms (RT) with standard errors (SE) and mean error rates (%E) for Experiment 1, as a function of target and singleton presence and target type

		Singleton condition						Effect size	
		Absent (A)			Present (P)			(P-A)	
Target type	Target	RT	SE	%E	RT	SE	%E	RT	%
High intensity	Absent	**310**	29	0.9	**351**	36	2.0	**41**	1.1
	Present	**293**	23	2.5	**302**	28	2.3	**9**	-0.2
Low intensity	Absent	**238**	29	3.5	**300**	36	5.0	**62**	1.5
	Present	**254**	23	7.0	**282**	28	11.8	**28**	4.8

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

There was also a trend towards an interaction between target presence and the target type [F(1,14) = 4.40, *MSE* = 4267.19, p = .055] such that the main effect of target presence was only found when the target was loud (*M* (target absent) = 331 ms, *M* (target present) = 298 ms), and not when the target was quiet (*M* (target absent) = 269 ms, *M* (target present) = 268 ms). This result is discussed following the report of the error rate analyses as these showed an opposite trend. No other interactions reached significance ($p > .20$ for all comparisons).[2]

Errors A three-way mixed model ANOVA with the within-subjects factors of singleton presence (vs. absence) and target presence (vs. absence) and the between-subjects factor of target type (high vs. low intensity) was also run on the error rates. Although the main effect of singleton presence did not reach significance [$F(1,14) = 3.30$, *MSE* = 50.77, $p = .091$], there was a trend for higher error rates when the singleton was present (*M* = 5.3%) versus absent (*M* = 3.5%), consistent with the RTs. There was a significant main effect of target presence [$F(1,14) = 17.73$, *MSE* = 147.02, $p < .01$] such that error rates were higher in the presence (*M* = 5.9%) versus absence of the target (*M* = 2.8%). This may reflect a trade-off with the RTs, such that although subjects are slower to respond when the target is absent, they are also more accurate in this condition.

There was also a main effect of target type [$F(1,14) = 10.29$, *MSE* = 385.14, $p < .01$] indicating that error rates were higher when the target was of low intensity (*M* = 5.9%) than when it was of high intensity (*M* = 2.8%). It is perhaps unsurprising that low intensity targets are harder to detect than targets of high intensity. However, this main effect of target type was qualified by a significant interaction with target presence [$F(1,14) = 8.46$, *MSE* = 70.14, $p < .05$]. Unlike the RT results, detection accuracy for quiet targets was affected by whether the target was present (*M* = 9.4%) or absent (*M* = 4.3%) so that misses were more likely than false alarms, whereas detection accuracy

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[2] Because Experiments 1-4 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 the singleton's position in the sequence.

for loud targets was less affected by whether the target was present (*M* = 2.4%) or absent (*M* = 1.4%), so that misses were about as likely as false alarms. Thus, although detection RTs for quiet targets were unaffected by target presence (vs. absence), this factor did have an effect on detection accuracy (with subjects making more misses than false alarms). By contrast, for loud targets the effects of target presence (vs. absence) were found on RTs but not on errors. This pattern might simply reflect greater data limits in the input for quiet targets (leading to misses because of greater difficulty in detecting low intensity targets) with performance in the case of loud targets only suffering from resource limits (e.g. slower search RTs when the target is absent and more stimuli must be searched). The other two-way interactions were not significant ($p > .20$ in both comparisons), and the three-way interaction did not reach significance either [$F(1,14) = 3.55$, *MSE* = 21.39, $p = .080$].[3]

Overall, this experiment has shown that the presence of an irrelevant high frequency singleton slows down detection of both high and low intensity targets in auditory search. This result is similar to previous studies demonstrating interference from irrelevant visual singletons in visual search tasks (e.g. Jonides & Yantis, 1988; Theeuwes, 1992).

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[3] The non-significant trend ($p = .08$) towards a three-way interaction hinted that the singleton effect for loud targets was greater when the target was absent than present (as found in the RTs) whereas the singleton effect for quiet targets was more pronounced when the target was present than absent. In other words, the presence of the singleton was more likely to lead subjects to miss the quiet target when it was present than to make them respond with a false alarm when it was absent. Again, this may reflect the fact that detection of quiet targets overall suffers more from misses than from false alarms, and thus misses are more affected than false alarms by singleton presence.

2.3 Experiment 2

It is possible that interference caused by singletons of higher frequency than the other sounds could be due to lower-level perceptual factors, rather than auditory AC. In particular, the singleton interference observed in Experiment 1 could have been due to masking effects of the singleton on the target sound. Although research into auditory masking has mainly examined masking effects of two simultaneous sounds on each other, it is also possible to observe masking effects from two non-simultaneous sounds (as in the present experiments)[4]. Non-simultaneous sounds can produce both forwards masking (when the first of two successive sounds masks the second) and backwards masking (when the second of two successive sounds masks the first). Although, unlike simultaneous masking, non-simultaneous masking does not eliminate perception of the masked sound, some partial masking effects (in which the perceived loudness of the masked sound is reduced, without it becoming completely inaudible) are still likely to occur (e.g. Scharf, 1971). Such masking can occur for up to 100 ms after the onset or offset of the masking sound, an interval longer than the ISIs used in the present experiments. There is evidence that partial masking increases both with increased intensity (e.g. Stevens & Guirao, 1967) and, at the loudness levels used here, with increased frequency (e.g. Scharf, 1971)[5]. As such, the high frequency singletons used in Experiment 1 might have had some masking effects on the lower frequency target

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[4] As the present thesis deals only with cases of non-simultaneous masking, my consideration of masking is restricted to energetic masking (i.e. masking due to physical interactions between the sounds). Informational masking (i.e. masking that cannot be attributed to physical interactions) is not considered because it only occurs for sounds presented simultaneously (e.g. Pollack, 1975).

[5] Although note that as the level of masking increases towards complete masking, the asymmetry reverses so that low frequencies become more masking than high frequencies (e.g. Wegel & Lane, 1924).

and nontargets (at least for the half of the subjects that had targets of lower intensity than the other sounds: the other half had targets with higher intensity and these would have been less likely to have been masked). Thus masking effects of the singleton may have contributed towards the singleton interference observed in Experiment 1. In order to control for potential alternative accounts in terms of masking effects, the purpose of Experiment 2 was to examine whether the interference effects observed in Experiment 1 due to high frequency singletons could generalize to singletons that are of lower frequency than the other sounds. If interference is found due to low frequency singletons, this will not be open to explanations in terms of lower-level factors such as masking.

2.3.1 Method

Subjects Sixteen new subjects participated in the experiment.

Stimuli & Procedure The stimuli and procedure were the same as in Experiment 1, except that the singleton distractor was presented at a lower frequency (440 Hz) than the targets and nontargets (520 Hz). All other aspects of the method were the same as in Experiment 1.

2.3.2 Results and Discussion

RTs Table 2 presents mean RTs and error rates across subjects as a function of singleton presence (vs. absence), target presence (vs. absence) and target type (high vs. low intensity). In line with the findings of the previous experiment, the three-way mixed model RT ANOVA using these factors revealed a significant effect of singleton presence [F(1,14) = 13.07, *MSE* = 36512.04, p < .01] indicating that target responses were slower when the singleton was present (*M* = 376 ms) versus absent (*M* = 328 ms). Also as in Experiment 1 (and previous visual search studies), there was a significant effect of target presence [F(1,14) = 10.63, *MSE* = 24004.47, p < .01] indicating slower responses on target absent (*M* = 372 ms) versus target present trials (*M* = 333 ms). There was no main effect of target type [F < 1].

As in Experiment 1, there was an interaction between singleton presence and target presence [F(1,14) = 16.88, *MSE* = 28130.42, p < .01] indicating that the singleton produced interference when the target was absent (mean interference effect = 90 ms) but not when it was present (mean effect = 5 ms). This finding suggests that interference from the low frequency singletons used in the present experiment might be more dependent on the absence of the target than interference from the high frequency singletons used in Experiment 1, in which interference effects (although weaker than in target absent trials) were still found in target present trials. This may be because high frequency singletons are stronger competitors for attention than low frequency singletons (an issue that will be explored further in Chapter 3). Although there appeared to be a numerical trend for a larger singleton effect when the target was of low intensity than when it was of high intensity (see Table 2), the factors of singleton presence and target type did not interact significantly (F < 1).[6] No other interactions reached significance (p > .20 in both comparisons).

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[6] A closer inspection of the individual data indicated that the numerical trend was mainly due to three of the 16 subjects showing unusually large singleton interference effects (over 200 ms) when the low intensity target was absent.

Table 2

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

		Singleton condition						Effect size	
		Absent (A)			Present (P)			(P-A)	
Target type	Target	RT	SE	%E	RT	SE	%E	RT	%
High intensity	Absent	**310**	42	5.4	**376**	62	9.1	**66**	3.7
	Present	**297**	38	9.0	**303**	41	6.8	**6**	-2.2
Low intensity	Absent	**344**	42	3.6	**457**	62	8.3	**113**	4.7
	Present	**363**	38	6.1	**369**	41	7.8	**6**	1.7

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

Errors A three-way mixed model ANOVA with the within-subjects factors of singleton presence (vs. absence) and target presence (vs. absence) and the between-subjects factor of target type (high vs. low intensity) was also run on the error rates. This revealed a trend for higher error rates when the singleton was present ($M = 8.0\%$) than when it was absent [$M = 6.0\%$, F(1,14) = 4.09, $MSE = 60.06$, p = .063]. No other main effects reached significance (p > .20 in both comparisons).

Once again, there was an interaction between singleton presence and target presence [F(1,14) = 9.07, $MSE = 81.00$, p < .01], indicating, in line with the RT results, that the singleton interference observed on target absent trials (mean interference effect = 4.2%, t(15) = 3.44, p < .01) did not occur on target present trials (mean effect = -0.3%). No other interactions reached significance (p > .20 in all comparisons).

In conclusion, the present experiment provides further evidence that a unique yet irrelevant singleton item slows RTs in an auditory detection task, consistent with the hypothesis that auditory singletons can capture attention. This effect cannot be explained in terms of masking by the singleton sound, as the lower frequency singletons used in the present experiment should have produced smaller masking effects than the other sounds.

2.4 Experiment 3

Experiments 1 and 2 have found interference effects due to irrelevant singleton distractors of both higher and lower frequency than the other nontargets. The following two experiments ask whether these interference effects can generalise to singletons that are unique on the dimension of intensity.

Targets were now defined by frequency. For half the subjects, targets were of higher frequency than nontargets and for the other half of subjects, targets were of lower frequency than nontargets. On half of the trials, one of the nontarget sounds was presented at a higher intensity than the other sounds. If the interference effects found in the previous two experiments reflect AC by singleton sounds in general, rather than being specific to changes in stimulus frequency, then the presence (vs. absence) of an intensity singleton should also produce a cost, despite that singleton being irrelevant to the task.

2.4.1 Method

Subjects Sixteen new subjects took part in the experiment.

Stimuli & Procedure Targets in the present experiment were defined by frequency, being of higher frequency (520 Hz) than nontargets (440 Hz) for half of the subjects and lower frequency (440 Hz) than nontargets (520 Hz) for the other half of the subjects. The singleton distractor was presented at the nontarget frequency with a higher intensity (approximately 83 dB SPL) than the rest of the sounds (approximately 72 dB SPL). All other aspects of the method were the same as in Experiment 1.

2.4.2 Results and Discussion

RTs Table 3 presents mean RTs and error rates across subjects as a function of singleton presence (vs. absence), target presence (vs. absence) and target type (high vs. low frequency). A three-way mixed model ANOVA using these factors revealed a significant effect of singleton presence [F(1,14) = 23.14, *MSE* = 26578.37, p < .01]. Consistent with the findings of both previous experiments, target RTs were slower in the presence (*M* = 301 ms) than in the absence of a singleton distractor (*M* = 260 ms, see Table 3). This finding suggests that irrelevant singleton distractors defined by intensity can capture attention, disrupting performance on a frequency detection task. There were no main effects of target presence or target type (F < 1 for both comparisons).

Table 3
Averages of subjects' mean RTs in ms (RT) with standard errors (SE) and mean error rates (%E) for Experiment 3, as a function of target and singleton presence and target type

		Singleton condition						Effect size	
		Absent (A)			Present (P)			(P-A)	
Target type	Target	RT	SE	%E	RT	SE	%E	RT	%
High frequency	Absent	**250**	31	0.6	**313**	47	1.8	**63**	1.2
	Present	**276**	39	1.4	**287**	43	2.8	**11**	1.4
Low frequency	Absent	**239**	31	2.4	**310**	47	5.4	**71**	3.0
	Present	**275**	39	3.5	**292**	43	5.1	**17**	1.6

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

As in both previous experiments, there was a significant interaction between singleton presence and target presence, [F(1,7) = 20.10, *MSE* = 11150.57, p < .01], reflecting a stronger effect of singleton presence on target absent trials (mean interference effect = 67 ms) than on target present trials (mean effect = 15 ms), although the weaker effect of singleton presence on target present trials was nevertheless significant [t(15) = 3.47, p < .01]. No other interactions reached significance (F(1,14) < 1 for all comparisons).

Errors A similar ANOVA run on the errors revealed a main effect of singleton presence [F(1,14) = 11.20, *MSE* = 50.77, p < .01]. In line with the RTs, error rates were higher when the singleton was present (*M* = 3.8%) than absent (*M* = 2.0%). No other effects or interactions reached significance (p > .15 in all comparisons).

In conclusion, the present experiment has shown that the singleton interference effect can generalise to a task where singletons and targets are defined on different dimensions from Experiments 1 and 2. This is important in suggesting that the interference reflects higher-level processes such as AC, rather than lower-level factors associated with the presence of a frequency singleton in an intensity discrimination task.

2.5 Experiment 4

As Experiment 3 used high intensity singletons, it was important to rule out alternative accounts for the singleton interference observed, either in terms of greater masking of the target by higher intensity singletons than by lower intensity nontargets (e.g. Stevens

& Guirao, 1967), or in terms of a startling effect due to the presence of a sound of higher intensity (e.g. Davis, Gendelman, Tischler & Gendelman, 1982). The present experiment used singletons that were of lower intensity than the nontargets so that any interference found due to these singletons would not be open to explanations in terms of lower-level factors such as masking or startling.

2.5.1 Method

Subjects Sixteen new subjects participated in this experiment.

Stimuli & Procedure The stimuli and procedure were the same as in Experiment 3 except that the singleton distractor was now 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 1.

2.5.2 Results and Discussion

RTs Table 4 presents mean RTs and error rates across subjects as a function of singleton presence (vs. absence), target presence (vs. absence) and target type (high vs. low frequency). A three-way mixed model ANOVA using these factors revealed a significant effect of singleton presence [F(1,14) = 17.11, *MSE* = 17441.16, p < .01]. Consistent with the findings of all previous experiments, target RTs were slower when the singleton was present (*M* = 327 ms) than when it was absent (*M* = 294 ms). This is an important result, as the interference effect in the present experiment is due to singletons that were of lower intensity than the other sounds, and as such cannot be explained in terms of masking or startling effects of the singleton (as these effects should, if anything, be smaller for the low intensity singleton stimuli than for the nontarget stimuli, e.g. Stevens & Guirao, 1967). As in Experiments 1 and 2 (and previous visual search experiments), there was also a significant effect of target presence [F(1,14) = 4.59, *MSE* = 6442.47, p = .05] such that responses were slower when the target was absent (*M* = 321 ms) versus present (*M* = 301 ms). Although there was a numerical trend for faster RTs for the subjects detecting high frequency targets compared with subjects detecting low frequency targets (see Table 4), this trend was not statistically significant [F < 1].

Table 4

Averages of subjects' mean RTs in ms (RT) with standard errors (SE) and mean error rates (%E) for Experiment 4, as a function of target and singleton presence and target type

		Singleton condition						Effect size	
		Absent (A)			Present (P)			(P-A)	
Target type	Target	RT	SE	%E	RT	SE	%E	RT	%
High frequency	Absent	**266**	33	0.6	**333**	45	3.9	**67**	3.3
	Present	**276**	38	2.3	**272**	40	2.8	**-4**	0.5
Low frequency	Absent	**303**	33	2.1	**382**	45	8.1	**79**	6.0
	Present	**332**	38	3.3	**324**	40	3.6	**-8**	0.3

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

Once again, there was a significant interaction between singleton presence and target presence [F(1,14) = 28.38, *MSE* = 24588.59, p < .01]. As in previous experiments, the singleton had a stronger effect on target absent trials (mean interference effect = 72 ms) than on target present trials, where there was in fact no interference effect in the present experiment (mean effect = -6 ms). Thus, unlike the high intensity singletons used in Experiment 3, the low intensity singletons used in the present experiment did not cause interference when the target was present. This is similar to the case of frequency singletons, where high frequency singletons in Experiment 1 caused interference on target present and target absent trials, whereas the low intensity singletons of Experiment 2 interfered only on target absent trials. Thus high values on either frequency or intensity may be better able to compete for attention with the targets than low values. This may be because the high value singletons have greater salience (relative to the target) than low value singletons, but as I did not manipulate salience systematically, the data speak only indirectly to this issue. No other interactions reached significance ($p > .30$ in all comparisons).

Errors A similar ANOVA run on the error rates revealed a significant effect of singleton presence [$F(1,14) = 6.31$, $MSE = 102.52$, $p < .05$]. Consistent with the RTs, error rates were higher when the singleton was present ($M = 4.6\%$) versus absent ($M = 2.1\%$). No other main effects reached significance ($p > .20$ in both comparisons)

There was a trend towards an interaction between singleton presence and target presence [$F(1,14) = 4.02$, $MSE = 70.14$, $p = .065$], suggesting in line with the RT results that the singleton interference effect was greater on target absent trials (mean interference effect = 4.6%) than on target present trials (mean effect = 0.9%). No other interactions reached significance ($p > .20$ in all comparisons).

In conclusion, Experiment 4 has demonstrated that low intensity singletons can produce interference in an auditory target detection task. This finding is important as interference due to a lower intensity singleton cannot be explained in terms of the lower-level factors mentioned in association with the high intensity singletons in Experiment 3. Taken together, Experiments 3 and 4 therefore suggest that the singleton items capture attention because of their uniqueness, rather than because of some lower-level property associated with being of either lower or higher intensity than the other sounds.

2.6 Chapter discussion

The results of the experiments in this chapter are summarised in Figure 2. As shown in the figure, the presence of an irrelevant auditory feature singleton interfered with auditory detection tasks in all four experiments, resulting in longer RTs and in some cases increased error rates. This finding has generalised across singletons of high and low frequency and high and low intensity relative to the other sounds (as well as across detection tasks based on both intensity and frequency).

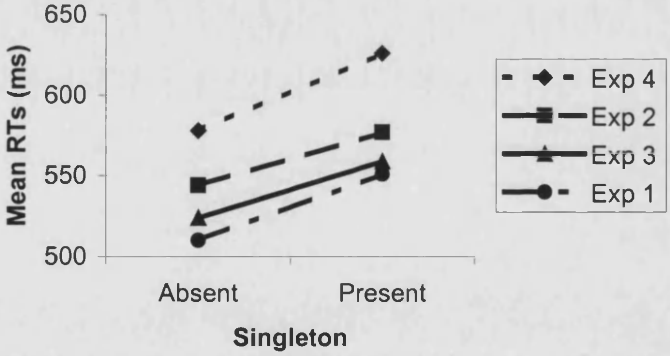

Figure 2: *Mean target RTs as a function of singleton presence for Experiments 1-4.*

In all four experiments singleton effects were greater when the target was absent than when it was present. The reduced or eliminated singleton cost on target present trials may be due to competition for attention between the target and distractor.

Interestingly, singleton costs were only eliminated for the low frequency and low intensity singletons, whereas high frequency and high intensity singletons produced a cost even on target present trials. This may be because the high value singletons have greater salience (relative to the target) than low value singletons, and are therefore stronger competitors for attention. However I did not manipulate salience systematically, and as such the data do not address this issue directly.

Chapter 3

Effects of irrelevant auditory singletons on target discrimination during auditory search

3.1 Introduction

The purpose of the present experiments was to extend the observations of singleton effects to a new search task. The experiments reported in Chapter 2 used auditory detection tasks because visual search studies, including the early research into visual AC, typically use tasks involving detection of target presence (vs. absence; e.g. Jonides & Yantis, 1988; Yantis & Jonides, 1984). However, visual AC has also been examined within a search plus discrimination task, developed by Theeuwes (e.g. 1991a; 1992) in which, for example, a shape target is present on each trial and subjects are asked to discriminate the orientation of a line contained within the shape. The present experiments were designed to ask whether irrelevant singleton distractors could interfere in an auditory task that is similar to this discrimination task.

In the discrimination task used here, one of two unique targets was present on each trial and the task was to indicate which of the two targets appeared. Note that, in this way the present discrimination design differs slightly from that of Theeuwes (e.g. 1991a, 1992). In his tasks, the target-defining feature (i.e. shape in the above example) was different from the reported target feature (i.e. line orientation). By contrast, in the present design subjects respond to target-defining feature itself (e.g. in a task where the target is defined as being of a different intensity from the nontargets, subjects' responses are also made according to the intensity of the target). This slight change to Theeuwes's design was made in order to avoid the need for manipulation of a third auditory feature dimension in the discrimination tasks, so that they would remain as similar as possible to the detection tasks described in Chapter 2 to allow for easy comparison between the two sets of experiments. Note, however, that Chapter 5 uses a discrimination design in which the target- and response-defining attributes are different, as in Theeuwes's visual tasks.

As in the previous experiments (and in Theeuwes's visual studies) a feature singleton defined on an irrelevant dimension, was presented on 50% of trials. Target performance was then analysed as a function of singleton presence (vs. absence).

As well as generalising the singleton effect to another type of task, the discrimination task used here has two other potential advantages. Firstly, recall that the experiments presented in Chapter 2 found a reliable interaction between the factors of singleton presence and target presence, such that the effect of singleton presence was greater when the target was absent than when the target was present. Indeed the interference effects of the low value frequency and intensity singletons used in Experiments 2 and 4 were eliminated completely when the target was present. The discrimination design will provide a further test of whether interference effects due to both high and low value singletons can be found when the target is present. As the target is present on every trial, this design will have greater experimental power and should therefore be more sensitive in either detecting or ruling out any such singleton effects.

A second advantage of the discrimination design is that it may be less open to an "odd-one-out" search strategy. Experiments 1-4 are open to the criticism that the task of detecting the presence of a unique target might encourage subjects to listen for any unique sound, rather than focusing on the relevant dimension. In other words, the detection task used in Chapter 2 may have encouraged subjects to adopt an "odd-one-out" detection strategy, making it harder for them to avoid distraction by irrelevant "odd-one-out" stimuli such as the singleton. The discrimination design used in the present experiments would seem less likely to encourage an "odd-one-out" strategy, as 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. This issue will be addressed more fully in Chapter 5.

3.2 Experiment 5

In Experiment 5, subjects searched sequences of five sounds for targets that were defined by intensity. A target was present on each trial and subjects were asked to make a speeded discrimination as to whether the target was of higher or lower intensity than the nontargets. Singletons were presented on half the trials at the nontarget intensity and differed from nontargets on the irrelevant dimension of frequency, being of higher frequency than targets and nontargets. If these irrelevant singletons capture attention despite being irrelevant to the discrimination task, this should lead to interference in performance on singleton present trials compared with performance on singleton absent trials.

3.2.1 Method

Subjects Eight new subjects took part in the experiment.

Apparatus and stimuli The equipment used was the same as in Experiment 1. 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). As in Experiment 1, 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).

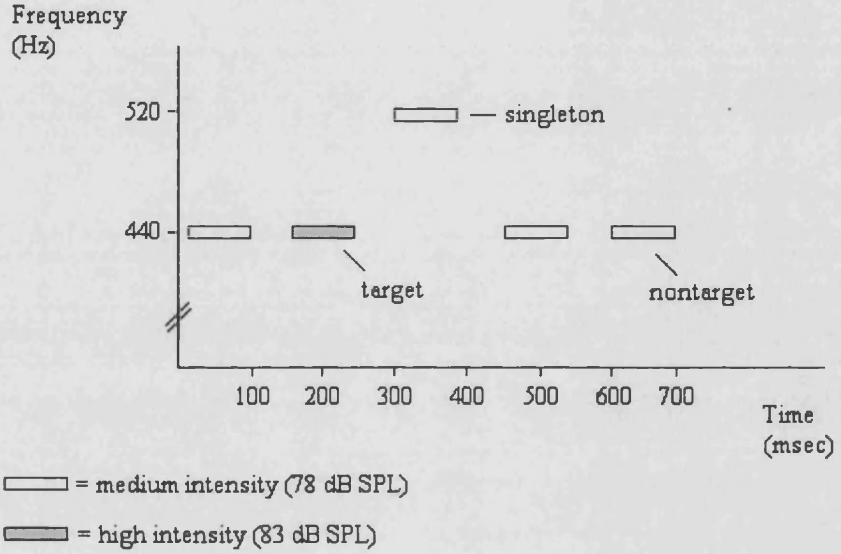

Figure 3: *schematic representation of an example trial from Experiment 5.*
The figure shows an example of a trial where the target is of high intensity. As described in the method (section 3.2.1), the target was of low intensity on 50% of trials. Similarly, the figure shows a trial where the singleton is present, but the singleton was just as likely to be absent. Finally, the singleton was equally likely to appear before the target as after the target (shown here).

Design & Procedure The design and procedure were similar to those of Experiment 1, except for the following changes. 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.[7] Subjects were told that a target would always be present, and responded “1” or “2” at the end of each stream according to which of the

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[7] Target positions were restricted in this way to allow for sufficient observations for an analysis of the effects of whether the singleton appeared before or after the target.

two possible targets they had heard. Targets were just as likely to be of high intensity as of low. The irrelevant distractor singleton appeared on 50% of trials, directly before or after the target with equal probability.[8] A 96 trial block included a fully-counterbalanced mix of the factors of singleton presence, singleton position and target position and their combinations. Two practice blocks of 16 trials each preceded the six experimental blocks.

3.2.2 Results and Discussion

RTs Table 5 presents mean RTs and error rates across subjects as a function of singleton presence (vs. absence) and target type (high vs. low intensity). A two-way within-subjects ANOVA using these factors revealed a significant main effect of singleton presence [F(1,7) = 9.68, *MSE* = 23490.82, p < .05]. As in all previous experiments, target RTs were slower in the presence (*M* = 312 ms) than in the absence (*M* = 257 ms) of the singleton distractor, see Table 5. Thus Experiment 5 has replicated the singleton interference effect within a discrimination design. There was no main effect of target type and no interaction between the two factors (F < 1 for both comparisons).

A one-way within-subjects ANOVA on the data from singleton present trials with the factor of singleton position (before vs. after the target) revealed a non-significant trend for a larger effect of singletons occurring before (*M* = 334 ms) rather than after the target (*M* = 295 ms), [F(1,7) = 3.81, *MSE* = 1569.72, p = .09]. This may

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[8] The singleton was restricted to appearing directly before or after the singleton so that there would be enough observations to allow for an analysis of the effects of singleton position (before versus after the target).

suggest that singletons occurring before the target compete more strongly for attention than those occurring after the target. However as the trend was not significant it cannot support a firm conclusion about the effects of singleton position.

Table 5

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

	Singleton condition						Effect size	
	Absent (A)			Present (P)			(P-A)	
Target type	RT	SE	%E	RT	SE	%E	RT	%E
High int.	**253**	27	11	**315**	32	13	**62**	2
Low int.	**263**	22	10	**309**	36	22	**46**	12

Errors In line with the RTs, a two-way ANOVA run on the error rates with the factors of singleton presence (vs. absence) and target type (high vs. low intensity) also found a significant main effect of singleton presence [F(1,7) = 18.55, *MSE* = .0413, p < .01], reflecting higher error rates on singleton present (*M* = 17%) versus singleton absent trials (*M* = 10%). There was a trend to suggest that error rates were higher when the target was of low intensity (*M* = 16%) than when it was of high intensity (*M* = 12%), however this trend was not significant [F(1,7) = 4.55, *MSE* = .0116, p = .07]. There was no interaction between singleton presence and target type [F(1,7) = 2.53, p = .16].

A one-way within-subjects ANOVA on the data from singleton present trials with the factor of singleton position (before vs. after the target) revealed a significant effect of singleton position [F (1, 7) = 12.92, *MSE* = .00534, p < .01]. Error rates were greater when the singleton occurred before (*M* = 24%) versus after the target (*M* = 11%). In fact, error rates when the singleton appeared after the target were similar to error rates in the singleton absent condition (*M* = 10%). This result seems to indicate that AC might be more likely to disrupt target perception when the singleton occurs before the target than when it occurs after the target (and early perceptual processing of the target has progressed without competition).

In conclusion, Experiment 5 has replicated the singleton interference effects found in Chapter 2 using a discrimination task rather than a detection task. This is an important result, as it shows that the singleton effect can generalise across two different tasks and as such suggests that the effect cannot be ascribed to the particular set-up used in the detection experiments but rather reflects a more general process such as auditory AC.

The present experiment was also important in demonstrating reliable interference in a task in which the target is always present (recall that the experiments presented in Chapter 2 found reliable interactions such that the singleton effect was stronger on target absent versus target present trials).

3.3 Experiment 6

The previous experiment found a significant cost due to the presence of high frequency singletons in an intensity discrimination task. The present experiment asks whether low frequency singletons can also produce interference in the same discrimination task. Note that if such interference were observed, it would not be open to explanations in terms of masking, as the lower frequency singletons should produce less masking than the nontargets.

3.3.1 Method

Subjects Eight new subjects took part in the experiment.

Stimuli and Procedure The stimuli and procedure were the same as in Experiment 5 except that the singleton distractor was presented at a lower frequency (440 Hz) than the targets and nontargets (520 Hz), as in Experiment 2. All other aspects of the method were the same as in Experiment 5.

3.3.2 Results and Discussion

RTs Table 6 presents mean RTs and error rates across subjects as a function of singleton presence (vs. absence) and target type (high vs. low intensity). As in previous experiments, the two-way within-subjects RT ANOVA with these two factors found a significant main effect of singleton presence [F(1,7) = 18.19, *MSE* = 12092.46, p < .01], indicating slower target RTs on singleton present (*M* = 289 ms) versus singleton absent trials (*M* = 251 ms, see Table 6). In line with Experiment 2 (Chapter 2), this suggests that the presence of a unique auditory distractor captures attention even when it is of lower frequency than the other sounds. However this finding extends the results of Experiment 2, to demonstrate interference due to a low frequency singleton on target present trials (recall that the singleton effect in Experiment 2 was only significant when the target was absent). There was no main effect of target type and no interaction between the two factors (F < 1 for both comparisons).

A one-way within-subjects ANOVA on the data from singleton present trials with the factor of singleton position (before vs. after the target) 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).

Table 6

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

	Singleton condition						Effect size	
	Absent (A)			Present (P)			(P-A)	
Target type	RT	SE	%E	RT	SE	%E	RT	%E
High int.	**248**	20	11	**292**	26	19	**44**	8
Low int.	**255**	17	14	**288**	18	14	**33**	0

Errors A two-way within-subjects ANOVA with the factors of singleton presence (vs. absence) and target type (high vs. low intensity) was also run on the error rates. This revealed a significant effect of singleton presence [F(1,7) = 9.31, *MSE* = .014, p < .05]. Consistent with the RTs error rates were higher on singleton present (*M* = 16%) versus singleton absent trials (*M* = 12%). There was no effect of target type and no interaction between the two factors (p > .20 for both comparisons).

A one-way within-subjects ANOVA on the error data from singleton present trials with the factor of singleton position (before vs. after the target) found a significant effect of singleton position [F(1,7) = 13.05, *MSE* = .00161, p < .01], suggesting in line with the previous experiment, 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%).

Overall the present experiment has demonstrated significant singleton interference due to low frequency singletons in a discrimination task. This result establishes interference due to low frequency singletons on target present trials (recall that Experiment 2 found no such effect) and is strongly suggestive of AC by the low frequency singletons, as the singleton interference cannot be accounted for in terms of masking.

3.4 Experiment 7

The purpose of Experiments 7 and 8 was to examine whether frequency discrimination tasks would be disrupted by singleton distractors defined on the irrelevant dimension of intensity. Subjects in the present experiment searched for a target sound that was always present and responded according to whether it was of higher or lower frequency than the intermediate nontargets. Singletons were presented on 50% of trials, at the same frequency as the nontargets but with a higher intensity.

3.4.1 Method

Subjects Ten new subjects took part in this experiment. One subject was replaced due to a very high error rate (50% errors).

Stimuli and procedure High frequency targets had a frequency of 520 Hz, low frequency targets had a frequency of 440 Hz and nontargets had an intermediate frequency of 480 Hz. As in Experiment 3, singletons were presented at the nontarget frequency (480 Hz) but were of higher intensity (approximately 83 dB SPL) than targets and nontargets (approximately 72 dB SPL). All other aspects of the method were the same as in Experiment 5.

3.4.2 Results and Discussion

RTs Table 7 presents mean RTs and error rates across subjects as a function of singleton presence (vs. absence) and target type (high vs. low frequency). A two-way within-subjects ANOVA using these factors revealed a significant main effect of singleton presence [F(1,9) = 7.71, *MSE* = 6916.11, p < .05]. As in all previous experiments, target RTs were slower on singleton present trials (*M* = 322 ms) versus singleton absent trials (*M* = 295 ms), in line with predictions of AC by the irrelevant singleton distractor. There was no main effect of target type (F < 1) but target type interacted with singleton presence [F(1,9) = 12.34, *MSE* = 8406.23, p < .01] such that the singleton interference effect was present only when the target was of low frequency and not when the target was of high frequency (see Table 7). Although this is a surprising result, the same high intensity singleton has already been shown to produce interference in detection of a high frequency target (Experiment 3) and, to anticipate somewhat, the following experiment will show that high frequency targets suffer from interference by low intensity singletons. Thus, the present finding is unlikely to be due either to high intensity singletons being incapable of capturing attention, or to high frequency targets being particularly resistant to AC. Instead, it seems more likely to be due to the particular combination of the high intensity singleton and high frequency target within this particular discrimination design. As this is the only experiment of eight (in Chapters 2 and 3) to produce an anomalous result of this kind, it did not seem worth pursuing.

There was no effect of singleton position (before vs. after the target, *M* = 322 ms for both singleton positions).

Table 7

Averages of subjects' mean RTs in ms (RT) with standard errors (SE) and mean error rates (%E) for Experiment 7, as a function of singleton presence and target type

	Singleton condition						Effect size	
	Absent (A)			Present (P)			(P-A)	
Target type	RT	SE	%E	RT	SE	%E	RT	%E
High freq.	**315**	41	11	**313**	34	11	**-2**	0
Low freq.	**277**	31	6	**332**	36	11	**55**	5

Errors A two-way within-subjects ANOVA run on the error rates with the factors of singleton presence (vs. absence) and target type (high vs. low frequency) revealed no significant main effects or interactions (p > .20 for all comparisons), although the numerical trends for singleton presence were similar to the RT results (see Table 7).

A one-way within-subjects ANOVA on the data from singleton present trials with the factor of singleton position (before vs. after the target) revealed no effect of singleton position (before (*M* = 12%) vs. after the target (*M* = 10%), F(1,9) < 1).

In conclusion, Experiment 7 has replicated the singleton interference effect found in all previous experiments using a high intensity singleton. This is important in generalising the effect to a task in which targets and singletons are defined on different dimensions than in Experiments 5 and 6. Although the high intensity singleton did not appear to interfere with discrimination of high frequency targets, this appears to be an anomalous result when considered in conjunction with the results of the seven other experiments in Chapters 2 and 3.

3.5 Experiment 8

In this experiment I examine the effects of singletons that are of lower intensity than the other sounds. Because lower intensity singletons should, if anything, produce less masking than the nontargets, any interference effect found will not be open to accounts in terms of masking.

3.5.1 Method

Subjects Eight new subjects took part in the experiment. Four were replaced due error rates of 48%, 32%, 21% and 20%, all of which were over 3 SDs from the group mean of 6% (calculated with these subjects excluded).

Stimuli & Procedure The stimuli and procedure were the same as in Experiment 7 except that, as in Experiment 4, the singleton distractor was presented with a lower intensity (approximately 72 dB SPL) than targets and non-targets (approximately 83 dB SPL). All other aspects of the method were the same as in Experiment 7.

3.5.2 Results and Discussion

RTs Table 8 presents mean RTs and error rates across subjects as a function of singleton presence (vs. absence) and target type (high vs. low frequency). As in previous experiments, the two-way within-subjects RT ANOVA using these factors revealed a significant main effect of singleton presence [F(1,7) = 10.27, *MSE* = 1430.99, p < .05], reflecting slower target RTs on singleton present (*M* = 262 ms) versus singleton absent trials (*M* = 249 ms). In line with Experiment 4 (Chapter 2) this suggests that a singleton that is of lower intensity than the other sounds can nevertheless capture attention despite being irrelevant to the task. As well as ruling out accounts in terms of masking (as a singleton of lower intensity than the nontargets would produce less masking than each nontarget), this result also establishes interference due to low intensity singletons in the presence of the target (recall that the low intensity singletons used in Experiment 4 only caused significant interference on target absent trials).

There was no main effect of target type and, in a change from Experiment 7, there was no interaction between singleton presence and target type (F < 1 for both comparisons). In other words, a singleton effect was now found for both high and low frequency targets (see Table 8), whereas in Experiment 7 the effect only appeared on trials where the target was of low frequency.

A one-way within-subjects ANOVA on the data from singleton present trials with the factor of singleton position (before vs. after the target) revealed no effect of singleton position in the RTs (before (*M* = 261 ms) vs. after the target (*M* = 263 ms), F < 1).

Table 8

Averages of subjects' mean RTs in ms (RT) with standard errors (SE) and mean error rates (%E) for Experiment 8, as a function of singleton presence and target type

	Singleton condition						Effect size	
	Absent (A)			Present (P)			(P-A)	
Target type	RT	SE	%E	RT	SE	%E	RT	%E
High freq.	**252**	38	5	**269**	39	5	**17**	0
Low freq.	**246**	24	6	**256**	26	7	**10**	1

Errors A two-way error ANOVA with the within-subjects factors of singleton presence (vs. absence) and target type (high vs. low frequency) found no significant effects or interactions (p > .30 for all comparisons). However the subsequent one-way within-subjects ANOVA on the data from singleton present trials with the factor of singleton position (before vs. after the target) revealed a significant effect [F(1,7) = 7.62, *MSE* = .00064, p < .05]. As in Experiments 5 and 6, error rates were higher when the singleton occurred before (*M* = 8%) as opposed to after the target (*M* = 5%), and error rates in the singleton after target condition were similar to error rates in the singleton absent condition (*M* = 6%).

In conclusion, Experiment 8 has replicated the singleton interference effect found in Experiment 7 using low (rather than high) intensity singletons. This is an important result as it clearly establishes interference due to low intensity singletons on target present trials (recall that Experiment 4, Chapter 2 found no effect of low intensity singletons when the target was present). This result is strongly suggestive of AC by the low intensity singletons, as it cannot be explained in terms of masking of the target.

3.6 Chapter discussion

The experiments reported in this chapter have shown clear interference effects due to the presence of an irrelevant feature singleton in an auditory search and discrimination task. As illustrated in Figure 4, this singleton interference has generalised across all different combinations of target and distractor frequency and intensity. Importantly, within each dimension, the singleton interference effect was found for both high and low singleton feature values. As accounts in terms of low-level interference due to high value singletons (e.g. masking) cannot apply to singletons that are specified as having lower features values than the other stimuli, these effects suggest that the singleton interference reflects higher-level attentional processes.

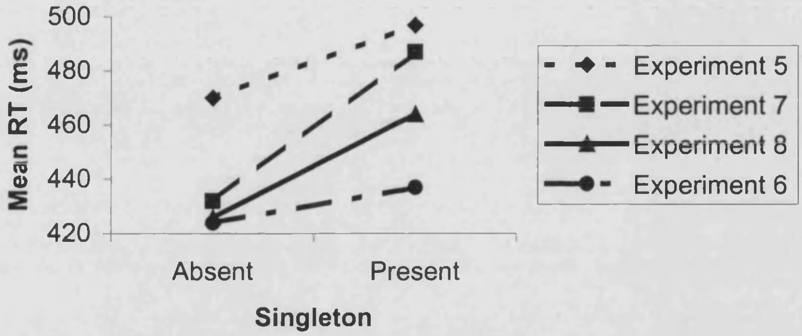

Figure 4: *Mean target RTs as a function of singleton presence (vs. absence) for Experiments 5-8.*

The experiments reported in Chapter 2 found singleton interference effects in detection tasks. The present experiments extend those findings to demonstrate that irrelevant singletons can also interfere with discrimination tasks. This is important, as in these experiments a unique target sound was present on each trial and therefore the presence of a unique sound alone could not inform the subject of the correct response. This should have encouraged subjects to attempt to differentiate between relevant and irrelevant singleton sounds, perhaps leaving them less open to AC. Nevertheless, with the exception of one of the eight combinations used (high frequency target and high intensity singleton), the presence of a singleton sound interfered with target responses, and this strengthens the claim that such singletons capture attention despite being clearly irrelevant to the task.

The present findings of singleton interference in discrimination tasks are also encouraging as they establish clear singleton effects in the presence of the target (recall that interference effects in the experiments in Chapter 2 were stronger on target absent versus target present trials). In fact, Experiments 2 and 4 failed to find any interference effect on target present trials due to singletons of low frequency and low intensity respectively. In this respect, Experiments 6 and 8 are especially important in demonstrating clear interference effects due to the same low value singletons when the target is present.

Finally, although there was no effect of singleton position on RTs, the presence of a singleton before the target appeared to be more detrimental to accuracy than the presence of a singleton after the target. This result may have occurred because AC is more likely to disrupt target perception, resulting in incorrect discrimination, when it occurs before the target than when it occurs after the target (in which case early perceptual processing of the target has progressed without competition). The following chapter investigates the effects of singleton position further.

Chapter 4

Effects of singleton position on target discrimination during auditory search

4.1 Introduction

The experiments in this chapter assess the effects of varying the position of the singleton feature within the auditory discrimination task described in Chapter 3. The experiments reported in Chapter 3 examined the effects of irrelevant singleton features occurring in distractor sounds that were presented immediately before or after the target sounds. By contrast, in the first experiment of this chapter I examine the effects of an irrelevant singleton feature that occurs within the target item itself. In the second experiment I ask whether singleton distractor interference can persist if the temporal separation of the singleton item relative to the target is varied (i.e. if the singleton is no longer restricted to occurring only directly before or after the target as it was in the experiments in Chapter 3). By varying singleton position in this way I will be able to test an important prediction of AC regarding the case of irrelevant singleton features that are presented within the target stimulus (Experiment 9). I will also be able to ask whether the singleton interference effect seen in previous experiments can generalise to singletons that are separated from the target by an intervening nontarget (Experiment 10).

4.2 Experiment 9

In Experiment 9 singleton position was varied so that the singleton feature could appear either within a nontarget stimulus (directly before or after the target as before) or within the target stimulus itself. This manipulation tests an important prediction of my account of previous singleton interference in terms of auditory AC. Whereas a singleton feature occurring within a nontarget item should produce a cost in search performance if it captures attention, as attention will be drawn to the irrelevant nontarget, a singleton feature occurring within the target item should facilitate performance, as attention should in this case be drawn to the relevant target. Recall that Jonides & Yantis (1988) demonstrated facilitation due to visual AC (i.e. the irrelevant singleton feature of abrupt-onset led to efficient search if it coincided with the target). The present experiment was designed to ask whether the auditory AC observed in previous chapters could also produce facilitation in this way.

Singletons were defined by frequency and, in a change from previous experiments, targets were defined by duration. The dimension of intensity was not used, as there are known to be interactions between the frequency and intensity of a particular sound. As mentioned previously, this interaction should not be noticeable over the particular ranges used here (see footnote 1, pg. 51). However, in the present experiment comparisons of the size of the singleton effect are made between the condition where the singleton feature is presented within the target sound (so that the singleton and target features could interact) and the condition where the singleton feature is presented within a nontarget sound (so that the two features can not interact). It was therefore especially important to avoid even slight interactions between the target and singleton dimensions, because such interactions would have had different effects in the different conditions. For this reason, the dimensions of duration and frequency were now used, as these dimensions are known to be independent (e.g. Allan & Kristofferson, 1974; Woods, Sorkin & Boggs, 1979). Were the present experiment to replicate previous findings of singleton interference, it would therefore generalise the interference effect to a new discrimination task in which targets are defined by duration, rather than frequency or intensity as in previous experiments.

Subjects searched for a target that was present on each trial, and responded according to whether it was of long or short duration. Non-targets were of medium duration. An irrelevant singleton feature, defined as a higher frequency than the targets and non-targets, was presented on two thirds of the trials. A high value singleton was used because there was some suggestion from the previous experiments that high value singletons produced stronger interference effects than low value singletons. Thus, were these reliable interference effects of high value singletons to be reversed to facilitation, simply by varying the position of the singleton feature in the sequence, this would provide a very convincing demonstration that the effects of such potent singletons are due to capture of attention, rather than to any lower-level factors (e.g. masking).

In a change from previous experiments the target sound itself contained the singleton feature on a third of trials. On another third of trials the singleton feature was presented in a non-target sound (as in previous experiments). The singleton feature was absent from the sequence on the remaining third of trials. If the high frequency singleton captures attention to the item within which it is presented, the presence (vs. absence) of a nontarget singleton should interfere with performance of the discrimination task as before. By contrast, the presence of a singleton that coincides with the target sound should lead to facilitation of performance, by comparison with singleton-absent trials.

4.2.1 Method

Subjects 18 new subjects took part in the experiment. One subject was replaced due to an error rate of 39% (over 3 SDs higher than the group mean of 8%).

Stimuli Targets were defined on the basis of duration. Long targets had durations of 150 ms, short targets lasted 50 ms, and nontargets (including singletons) had intermediate durations of 100 ms. 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.[9] Singletons were defined by frequency: whereas targets and nontargets were all of a low frequency (440 Hz), singletons were presented at the higher frequency of 520 Hz. All sounds had intensities of approximately 78 dB SPL.

Procedure Subjects searched a sequence of five sounds for a target tone of longer or shorter duration than the non-target tones. Targets appeared on every trial in either the third or fourth position with equal probability, and were just as likely to be longer in duration than the non-targets as shorter. Subjects were informed that a target would always be present and were asked to respond either "1" for "short target" or "2" for "long target". The high frequency singleton feature was presented in the target item on one third of trials. On another third of trials the singleton feature coincided with a distractor item (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

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[9] Pilot testing had suggested that a design in which all sounds were followed by the same length ISI meant that the time between successive sound onsets changed, producing an uneven rhythmical pattern. This encouraged subjects to focus on the overall rhythm of each sequence, rather than focusing specifically on the durations of each sound. In addition, there is research to suggest that subjects' judgements about sounds are more accurate if the sounds appear in rhythmically expected temporal positions than at unexpected ones (e.g. Jones, Moynihan, MacKenzie & Puente, 2002).

trial block included a fully-counterbalanced mix of the factors of singleton condition, target position and their combination. 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 1.

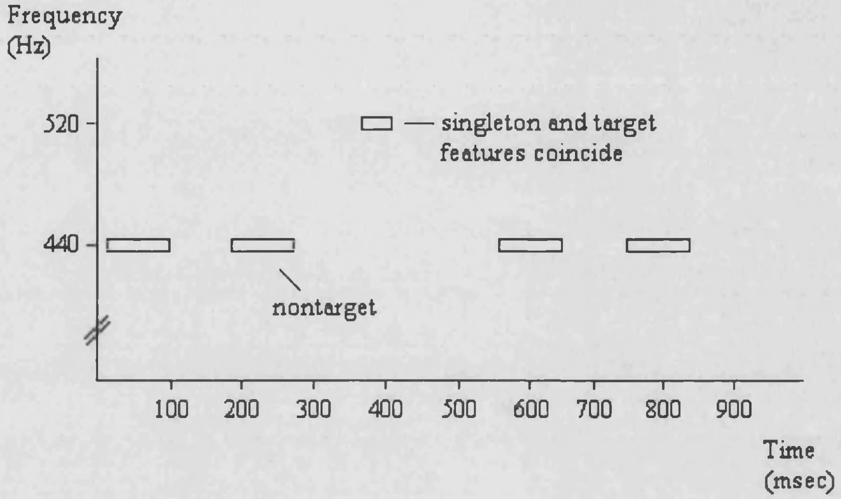

Figure 5: *schematic representation of an example trial from Experiment 9.*

The figure shows a trial where the target was of short duration. On the remaining 50% of trials the target was of long duration. The figure shows an example of a trial where the singleton and target features coincide within the same tone. This type of trial made up 33% of the total trials, as described in the method (section 4.1.1).

4.2.2 Results and Discussion

RTs Table 9 presents mean RTs and error rates across subjects as a function of singleton condition (absent; present in target; present in distractor) and target type (short vs. long duration). A two-way within-subjects ANOVA using these factors found a significant main effect of singleton condition [F(2,34) = 12.29, *MSE* = 26407.28, p < .01]. F-contrasts revealed that, by comparison with the singleton absent condition (*M* = 316 ms), RTs were significantly slower when the high frequency singleton feature coincided with a distractor sound [*M* = 343 ms, F(1,17) = 4.64, *MSE* = 2845.50, p <

.05] and significantly faster when the singleton feature coincided with the target sound [$M = 288$ ms, $F(1,17) = 7.98$, $MSE = 1469.72$, $p < .05$]. 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. There was also a main effect of target type such that RTs were slower when the target was of long duration ($M = 336$ ms) than of short duration [$M = 295$ ms, $F(1,17) = 29.02$, $MSE = 46025.75$, $p < .01$]. This finding is simply due to the fact that a short duration target will be identified as "short" at an earlier point in time than a long duration target will be identified as "long", and this will allow responses to be initiated earlier on trials where the target is short.

Table 9

Averages of participants' mean RTs in ms (RT) and mean error rates (%E), with standard errors (SE) for Experiment 9, as a function of singleton condition and target type

Target type	Singleton absent (A)			Singleton present in target (PT)			Facilitation effect size (A-PT)		Singleton present in distractor (PD)			Distraction effect size (PD-A)	
	RT	SE	%E	RT	SE	%E	RT	%E	RT	SE	%E	RT	%E
Short	**284**	37	4	**282**	43	4	**2**	0	**319**	49	12	**37**	8
Long	**347**	47	9	**295**	42	4	**52**	5	**366**	53	15	**71**	11

The factors of singleton condition and target type interacted significantly [$F(2,34) = 8.80$, $MSE = 5755.68$, $p < .01$] as shown in Table 9. Singleton effects were smaller in general for short targets than for long targets, and this difference was greater for the facilitation effects than for interference. This pattern appeared to suggest that there might be a floor effect for trials where the target was of short duration. Note however that, even though the facilitation effect was reduced for short targets compared with long targets, the effect did not reverse into interference. Rather, the faster RTs to short targets were simply not facilitated further by the irrelevant singleton.

As in previous experiments, a one-way within-subjects ANOVA on the data from singleton present trials with the factor of singleton position (before vs. after the target) found no significant effect of singleton position (before (M = 351 ms) vs. after the target (M = 333 ms), F(1,17) = 3.13, *MSE* = 1012.32, p = .10).

Errors In line with the RT analysis a two-way within-subjects error ANOVA with the factors of singleton condition (absent; present in target; present in distractor) and target type (short vs. long duration) found a significant main effect of singleton condition [F(2,34) = 17.95, *MSE* = .082, p < .01]. Also as in the RT analysis, F-contrasts revealed that, by comparison with the singleton absent condition (M = 7%), error rates were greater when the singleton feature coincided with a distractor [M = 13%, F(1,17) = 5.8, *MSE* = .00203, p < .05] and smaller when the singleton feature coincided with the target [M = 4%, F(1,17) = 19.65, *MSE* = .00407, p < .01]. Consistent with the RTs, there was also a significant main effect of target type [F(1,17) = 14.63, *MSE* = .022, p < .01] such that there were fewer errors when the target was of short duration (M = 7%) than of long duration (M = 9%). The two factors did not interact [F(2,34) = 2.44, *MSE* = .004, p = .10], although numerical trends were in line with the RTs, showing larger effects for long than short targets and more so for facilitation than interference (see Table 9).

As in previous experiments the one-way within-subjects ANOVA on the data from singleton present trials with the factor of singleton position (before vs. after the target) revealed a significant effect of singleton position in the error rates [F(1,17) =

18.15, *MSE* = .00467, p < .01] indicating that responses were less accurate when the singleton occurred before (*M* = 18%) vs. after the target (*M* = 8%), with the latter condition resulting in similar error rates to the singleton absent condition (*M* = 7%).

In conclusion, Experiment 9 has replicated the findings of the experiments in Chapters 2 and 3 in demonstrating a significant cost to both RTs and errors associated with the presence of an irrelevant feature singleton in an auditory search task. It has also generalised this singleton interference effect to a task in which targets are defined by duration. In addition, this experiment has found evidence for facilitation of responses when the singleton feature is 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.

This experiment also found that the facilitation effect, while strong on trials where the target was long, was absent on trials where the target was short. This appeared to reflect a floor effect for short targets, such that they were identified so quickly and accurately when the singleton was absent that there was no additional facilitation effect.

The facilitation effect demonstrated here rules out a potential alternative explanation of the singleton interference effects. As reviewed in the general introduction, there is evidence to suggest that auditory attention can be cued towards ranges of frequencies, intensities and durations. In a typical design, Mondor & Bregman (1994) asked subjects 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, than when the two were at different frequencies. Similar techniques have shown that auditory attention can also be drawn to previously cued intensity ranges (e.g. Leek, Brown and Dorman, 1991; Luce and Green, 1978; Mondor & Lacey, 2001; Nosofsky, 1983). This presents a potential problem for the discrimination tasks I have used, as they are likely to 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 observed 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 finding of facilitation due to the singleton cannot be explained in these terms. In fact, the target should be 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. Thus the present results cannot be explained in terms of expectancy.

The presence of a facilitation effect is inconsistent with Schröger & Wolff's (1998) finding that detection of targets defined by duration 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. The present task involved searching for a target sound within a short RSAP stream. In this design, stimuli must compete against each other for attentional resources and AC by a particular sound will provide it with a large processing advantage. By contrast, stimuli in Schröger & Wolff's (1998) study were separated by intervals of one second and thus did not have to compete with each other for attention. It therefore seems most likely that their findings reflect expectancy effects.

The contrast between the present results and those of Schröger and Wolff (1998) demonstrates the importance of behavioural research into auditory distraction, to go alongside the ERP research that has been carried out to date. Indeed, the present finding provides the first demonstration that deviant sounds (that might be expected to elicit both the MMN and the P3a responses) can lead to facilitation rather than interference in a concurrent task. For this reason, an interesting follow-up to the present study would have been to record ERPs from subjects carrying out the facilitation task, however this was unfortunately beyond the scope of the current thesis.

4.3 Experiment 10

The results of Experiment 9 are very encouraging for the hypothesis that an irrelevant auditory singleton can capture attention. The present experiment aims to characterise the effect further, by asking whether singleton interference can persist over a longer length of time than has been used in previous experiments. Here I compare the interference effects of singletons that are presented directly before or after the target, with the effects of singletons that are separated from the target by an intervening nontarget. If the auditory AC I have demonstrated in previous experiments lasts only for very short lengths of time, then interference effects would be eliminated when the singleton is separated from the target by an intervening nontarget. If, on the other hand, the process of AC is longer-lasting, the interference effect should persist despite such separation. In addition, were the singleton interference effect to persist in this way, this would provide further evidence the effect is unlikely to be to low-level interactions between adjacent sounds (e.g. masking).

4.3.1 Method

Subjects 10 new subjects 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. As in Experiment 9, 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.

Procedure Subjects 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. Subjects were asked to respond either "1" for "long target" or "2" for "short target". The singleton distractor appeared on 50% of trials, before or after the target with equal probability. On half of these singleton present trials, the singleton occurred directly before or after the target (I 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 mix of the following factors and their combinations: target position, target type (long or short duration), 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 9.

4.3.2 Results and Discussion

RTs Table 10 presents mean RTs and error rates across subjects as a function of singleton presence/separation (absent; present separation 0; present separation 1) and target type (short vs. long duration). A two-way ANOVA with the within-subjects factors of singleton presence (present vs. absent) and target type (short vs. long duration) revealed a significant main effect of singleton presence [F(1,9) = 10.24, *MSE* = 5974.85, p < .05]. In line with previous results, target RTs were slower in the presence (*M* = 325 ms) versus the absence (*M* = 301 ms) of the singleton distractor, suggesting that the singleton captured attention. There was also a significant effect of target type [F(1,9) = 14.12, *MSE* = 65782.64, p < .01], such that RTs were slower when the target was of long duration (*M* = 354 ms) versus short duration (*M* = 272 ms). As mentioned in the results section of Experiment 9, this result is unsurprising as subjects are able to start responding earlier after a short target than a long target. Although, as in Experiment 9, there was a numerical trend for smaller singleton effects overall for trials where the target was short rather than long (see Table 10), the factors of singleton presence and target type did not interact significantly (F < 1).

A further three-way ANOVA on RTs from singleton present trials with the within-subjects factors of singleton-target separation (0 vs. 1), singleton position (before vs. after the target) and target type (long vs. short duration) found no significant main effect of singleton-target separation [F(1,9) = 2.08, *MSE* = 3479.26, p = .183]. Thus the interference associated with singleton presence was just as strong for singletons that were separated from the target by an intervening nontarget (*M* = 333 ms) as for singletons that appeared directly before or after the target (*M* = 320 ms). This suggests that the process of auditory AC as observed in the current experiments can last over at least 270 ms and across an intervening item, as it persists even when the singleton is separated from the nontarget. As in the previous analysis, there was a main effect of target type indicating that responses were slower when the target was of long duration (*M* = 370 ms) than of short duration (*M* = 284 ms). There was no main effect of singleton position, and no significant interactions between any of the factors (p > .14 in all comparisons).

Table 10

Averages of participants' mean RTs in ms (RT) and mean error rates (%E), with standard errors (SE) for Experiment 10, as a function of singleton presence/separation from target, and target type

Target type	Singleton absent (A)			Singleton present Separation 0 (P0)			Effect size (P0-A)		Singleton present Separation 1 (P1)			Effect size (P1-A)	
	RT	SE	%E	RT	SE	%E	RT	%E	RT	SE	%E	RT	%E
Short	**264**	18	4	**281**	18	10	**17**	6	**286**	25	11	**22**	7
Long	**338**	31	10	**359**	39	9	**21**	-1	**380**	41	10	**42**	0

Errors The two-way error ANOVA using the factors of singleton presence (present vs. absent) and target type (short vs. long duration) revealed a significant effect of singleton presence [F(1,9) = 6.41, *MSE* = .0014, p < .05], such that error rates were higher when the singleton was present (*M* = 10%) versus absent (*M* = 7%), consistent with the RTs. There was no effect of target type and no interaction between the two factors (p > .15 in both comparisons).

The three-way ANOVA on error data from singleton present trials with the within-subjects factors of singleton-target separation (0 vs. 1), singleton position (before vs. after the target) and target type (long vs. short duration) indicated no difference between the effects of singletons with a separation of 0 (*M* = 10%) and those with a separation of 1 [*M* = 11%, F(1,9) = 1.01, *MSE* = 17.11, p = .34]. Thus, as in the RTs, the singleton sound interfered just as much with errors when it was separated from the target by an intervening nontarget as when it appeared directly before or after the target. As in previous experiments, there was a significant main effect of singleton position in the error rates [F(1,9) = 8.57, *MSE* = 714.01, p < .05] such that 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%). There was no main effect of target type, and none of the interactions reached significance (p > .15 in all comparisons).

Overall, Experiment 10 has found no difference between interference effects due to singletons that occurred adjacent to the target in the sound stream and effects due to singletons that were separated from the target by one intervening nontarget. This suggests that auditory AC can persist despite a singleton-target separation of 270 ms in which another object is presented.

The finding that the singleton interference can persist across an intervening nontarget item is similar to a finding from the visual AC study of Folk, Leber & Egeth (2002). As discussed in more detail in the general introduction (Chapter 1), Folk et al. (2002) found visual AC due to colour singletons in sequential RSVP streams. This singleton interference occurred due to singletons either directly before the target or two items before it. In other words, the visual AC they found also persisted across an intervening item.

4.4 Chapter conclusions

Experiments 9 and 10 have characterised the auditory AC effect further by varying the position of the singleton feature within the auditory discrimination task used throughout much of this thesis. Experiment 9 demonstrated that performance in this task could be facilitated if the singleton feature occurred within the target sound. In other words, the very same singleton feature can produce facilitation in one trial and interference in the next, depending on whether it is part of a target or a nontarget (as predicted by an AC account of the previous findings). Experiment 10 then showed that singleton interference could persist across an item that separates the singleton from the target in the sequence. This provides further evidence that the singleton interference observed here cannot be due to low-level interactions between adjacent sounds (as in this case the interference effect would not have been present when the target and singleton were separated by an intervening sound). Thus, in addition to the demonstrations in Chapters 2 and 3 of interference by low intensity singletons (which cannot be attributed to low-level masking effects) this experiment provides further support for an AC account of the singleton interference demonstrated here.

Chapter 5

Effects of search strategy on singleton interference

5.1 Introduction

The purpose of the experiments described within this chapter was to examine the AC account for singleton interference further by asking whether this interference depends on subjects' top-down strategies for allocation of attention. As discussed in the general introduction (Chapter 1), AC in visual search tasks has been shown to be dependent on the attentional allocation strategy adopted by the observer. Specifically, it seems that AC by irrelevant feature singletons can only occur if subjects adopt a singleton detection strategy, in which they allocate attention towards any singleton items in the search display. In most of the tasks used in the visual AC paradigm, this is an efficient search strategy as the target itself is a feature singleton. However a singleton detection strategy also leaves the search open to AC by irrelevant singletons. On the other hand, if subjects are prevented from using a singleton detection strategy, visual AC is eliminated. Bacon & Egeth (1994) found that AC by colour singletons was eliminated if the target was not a reliable form singleton (either by presenting more than one target in each array, or by including nontargets of several different forms). Under these circumstances, a singleton detection strategy cannot be of use in locating the target, as the target is no longer a singleton and as such would not be selected for attentional allocation by a singleton detection search. Thus it is likely that subjects adopt a more focused feature search strategy instead, in which they allocate attention only towards items with the specific target feature. As the singleton does not contain this target feature, it is not selected for attentional allocation and it therefore ceases to capture attention.

The present experiments ask whether the auditory AC demonstrated within this thesis is also dependent on subjects' top-down strategies for allocation of attention. As well as providing an interesting comparison between the visual and auditory versions of the AC effect, these experiments provide a further test of the AC account of auditory singleton effects. If the singleton cost is due to capture of attention, it should depend on whether attention is allocated to that singleton or not. Thus, if interference due to auditory singletons can be reduced or eliminated by forcing subjects to focus their attention on a particular target feature, this will imply that the interference effect found when subjects engage in less focused searches (as in all the previous experiments) depends on allocation of attention towards the singleton sound, as predicted by the AC account.

In order to examine this possibility, I used a manipulation based on one of those adopted by Bacon and Egeth (1994) to force subjects into a feature search mode for attentional allocation. Bacon and Egeth (1994, Experiment 3) prevented singleton detection mode in a shape detection task by including nontargets of several different shapes in the search array, so that the target was no longer a reliable shape singleton (and singleton detection mode was therefore prevented). Under these circumstances, Bacon and Egeth found no AC by colour singletons, presumably because subjects were forced into a focused feature search strategy. In a similar manipulation, the nontargets in Experiment 12 were made heterogeneous on the target-defining dimension (frequency). Nontargets had one of two different frequencies, so that the target was not a frequency singleton and as such could only be identified by a search that focused on its particular frequency (rather than by a singleton detection search). Experiment 12 asks whether preventing a singleton detection strategy in this way will eliminate auditory AC, as it does visual AC.

In order to follow Bacon and Egeth's paradigm as closely as possible, I also modified the auditory discrimination task to ensure that the manipulation of search strategy had an effect purely on search processes, without altering the response. Subjects searched for targets on the basis of frequency and based their discrimination responses on a different dimension (duration). Specifically, subjects searched for a target defined by a single, pre-specified feature (a frequency of 480 Hz among nontargets of 780 Hz and 180 Hz) and responded according to whether it was long or short. This modified auditory task provides a close analogue of Bacon and Egeth's task (as well as of the task used by Theeuwes, 1992, on which Bacon and Egeth's task was based), in which subjects search for a target defined by shape and discriminate between different orientations of lines contained within the shape.

As described above, the task required for Experiment 12 involves several changes from the task used in previous experiments. Experiment 11 was therefore run to verify that singleton interference would still be found in this new task. In Experiment 11, singleton detection mode remained available (because the target was presented among homogeneous nontargets at 780 Hz) but subjects searched for a pre-specified feature target (of 480 Hz) and carried out a discrimination task based on the duration of this target.

Although this modification of the task was initially adopted in order to allow comparison with Experiment 12, any finding of singleton interference in Experiment 11 will be interesting in itself. As the target-defining and response-defining features will now be different from each other, subjects will be forced into a compound search where the target-defining feature does not also provide information on the response to be made. It will be interesting to examine whether or not auditory AC can persist in this type of search (as it does in the visual domain, e.g. Theeuwes, 1992).

Note also that this modified design may already go some way towards encouraging subjects into more of a feature-based search than the previous discrimination experiments. Although in those experiments (Chapters 3 and 4), the target was always present, so the simple presence of a unique sound could not inform responses (cf. the detection task used in Chapter 2), the target was defined as having one of two extreme feature values, so subjects could have adopted a search for any higher or lower value (rather than focusing on the precise target feature). By contrast, in Experiment 11 the target is always defined by the same pre-specified feature (a frequency of 480 Hz) and as such this task would be likely to go some way towards encouraging a feature-based search. However, as the target feature is still a unique singleton, we should still expect attentional capture, even with this modified design.

Another difference between Experiment 11 and previous experiments is that the difference used here between the target frequency (480 Hz) and the nontarget frequency (780 Hz) was much larger than in previous experiments. This was necessary so that subjects could perform the task accurately in both experiments, as discussed in the method (section 5.2.1). This large feature difference between targets and nontargets is likely to have increased the salience of the targets relative to the singletons. According to Theeuwes's (1991a, 1992, 1994) salience model of visual AC, the relative salience of targets and singletons determines whether or not AC occurs:

irrelevant singletons will only capture attention if they are more salient than targets. The salience of the targets and singletons depends on the size of the featural differences they produce when compared with the background nontargets. According to the model, each feature dimension (e.g. form, colour etc.) is analysed preattentively, allowing identification of items that produce large featural differences when compared with the other items in the array. Attention is then directed to these items before others. In this way irrelevant singleton items can attract attention, but only if they produce larger featural differences than the target (i.e. if they are more "salient" than the target). Note that Theeuwes's model is based on a visual search task where targets and singletons are presented simultaneously. By contrast, the present experiments use sequential presentation of stimuli therefore it is uncertain whether a similar model would apply. Nevertheless, if stimulus salience were to be important for determining AC in the auditory domain, the targets used in the present experiment would produce larger differences on the target dimension (frequency) than targets used in previous experiments, and they would thus be more salient than previous targets. On the other hand, the singletons used here would be equally as salient as the high intensity singletons used in other experiments. This means that the singletons used in the present experiment would be less salient (relative to targets) than singletons in previous experiments. Thus, if stimulus salience plays a role in auditory AC, we may expect a reduced singleton effect in Experiment 11.

The fact that Experiment 11 is more likely to encourage a feature search mode than previous experiments, along with the likelihood that the target is more salient in Experiment 11 than before (reducing the salience of singletons relative to targets), suggests that singleton interference is likely to be reduced in Experiment 11 compared with previous experiments. For this reason, the present experiment uses the singleton/target combination that has produced the strongest and most reliable interference in the experiments carried out so far: high intensity singletons and targets that are of lower frequency than nontargets. This combination produced the strongest effect in Chapter 2 (44 ms) and the second strongest effect in Chapter 3 (55 ms).[10]

A final difference between Experiment 11 and the previous experiments is that, because all search items must be of either short or long duration (to allow for the duration discrimination aspect of the task), half the singletons in Experiment 11 are of short duration and half are of long duration. It is hard to predict how this might affect the strength of AC by the singletons. It is seems most likely that, as each type of singleton is now half as likely, each one might appear more novel, and the interference effect might therefore be strengthened compared with cases when there is only one type of singleton. On the other hand, general context effects of this sort (such as how probable each particular singleton is) might matter less than the feature differences used. If this were the case, variations in singleton duration would not be expected to affect the level of AC, as both singletons still involve the same feature difference on the singleton dimension (intensity).[11]

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[10] Although the combination of a high frequency singleton and high intensity target produced a stronger effect (62 ms, Experiment 5, Chapter 3), this combination produced the smallest effect in the detection experiments (25 ms, Experiment 1, Chapter 2).

[11] In the visual experiments of Bacon and Egeth (1994) the singleton also varied on the response dimension (line orientation). However the different features of visual objects are perceived as more easily separable than the different features of auditory objects (e.g. Wood, 1975). Thus the orientation of the line presented within the singleton object would not affect perception of the colour of that object. By contrast, in hearing, an object's features are perceived as harder to separate, and thus the duration of the sound affects perception of the entire sound. This factor will remain constant between Experiments 11 and 12, and should not affect the critical question of whether the singleton interference effect predicted in Experiment 11 will be eliminated in Experiment 12 when singleton detection strategy is prevented.

5.2 Experiment 11

In this experiment subjects searched a sequence of five tones for a target of lower frequency than the other tones. The low frequency target was present on every trial and subjects were asked to respond according to whether this target tone was of long or short duration. A high intensity singleton was present on half the trials. If this singleton captured attention despite being irrelevant to the task, it would produce a cost to performance on singleton present trials compared with singleton absent trials.

5.2.1 Method

Subjects 12 new subjects took part in the experiment. Two were replaced due to near-chance level performance (41% and 50% error rates). A third subject was replaced due to a mean RT (580 ms) that was over three SDs from the group mean (group *M* = 310 ms, SD = 48.7 ms).

Stimuli Targets were defined by frequency, being lower (480 Hz) than nontargets (780 Hz). Singletons were presented at the nontarget frequency (780 Hz) and were of higher intensity (approximately 85 dB SPL) than targets and nontargets (approximately 73 dB SPL). Because the task was to respond according to the duration of the target, all sounds could have durations of either 100 ms or 300 ms. As in Chapter 4, sounds were separated by different ISIs depending on their durations. The total duration of stimulus presentation and ISI was kept constant at 400 ms: sounds of 100 ms were followed by 300 ms ISIs and sounds of 300 ms were followed by 100 ms ISIs.

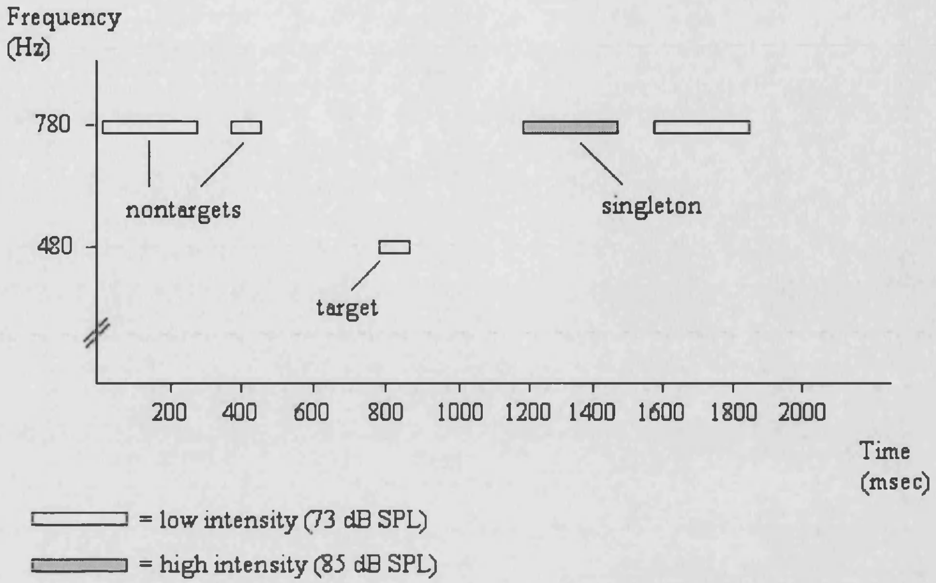

Figure 6: *schematic representation of an example trial from Experiment 11.*

Figure 6 shows an example of a trial where the target is of short duration. This type of trial made up 50% of the total trials; on the remaining 50% the target was of long duration, as described in the method (section 5.2.1). Note however that the target had a frequency of 480 Hz in every trial. Similarly, the figure shows a trial where the singleton is present (50% of trials). On the other 50% the singleton was absent. On half of these singleton present trials the singleton was of long duration (as shown), whereas on the other half the singleton was of short duration. Finally, the singleton is shown as appearing after the target but was equally likely to appear before the target.

Design and Procedure A low frequency target appeared on every trial in either the third or fourth position with equal probability, and was just as likely to be long in duration as short. Subjects responded according to the duration of the target sound, pressing “1” for “long target” or “2” for “short target” on the number keypad. A high intensity singleton appeared on 50% of trials. Singletons were of long or short duration with equal probability and were just as likely to occur before the target as after it. Nontarget durations were assigned at random, with the constraint that there was always one nontarget of short duration and one of long duration in every trial.

A 64 trial block included a fully-counterbalanced mix of the following factors and their combinations: target position, target duration (long or short), singleton presence, singleton position (before or after the target), singleton duration (long or short). Six experimental blocks were run, preceded by two practice blocks, each containing 16 trials. 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 practice block followed exactly the same procedure as the experimental blocks. All other aspects of the method were as described in Experiment 1.

5.2.2 Results and Discussion

RTs Table 11 presents mean RTs and error rates across subjects as a function of singleton presence (vs. absence) and target type (short vs. long duration). A two-way within-subjects ANOVA on the RTs using these factors revealed a significant main effect of singleton presence [F(1,11) = 8.72, *MSE* = 4478.18, p < .05] indicating that responses were slower when the singleton was present (*M* = 320 ms) than when it was absent (*M* = 301 ms). Thus the singleton interference effect can still be obtained if subjects respond to a non-defining attribute of the target, as in the visual experiments of Theeuwes (e.g. 1992). Note however that numerical trends suggest that the present singleton effect is smaller in magnitude (M = 19 ms) than the singleton effects previously obtained for this combination of high intensity singleton and low frequency target (44 ms in the detection task, Experiment 3, and 55 ms in the discrimination task, Experiment 7). As mentioned in the introduction, this may have occurred for one of two reasons. The design of the present experiment goes some way towards encouraging subjects towards adopting a feature-based search, as a target is always present (so the simple presence of a unique object cannot inform responses) and is always defined by a single feature (rather than changing from trial to trial). In addition, the targets used here were more salient than those used in previous experiments. Either of these factors (or a combination of the two) could explain the reduced singleton interference here. There was no main effect of target type [F(1,11) = 1.58, *MSE* = 1393.53, p = .24] and, despite a numerical trend to suggest that the singleton interference effect might be greater on trials where the target was long than on trials where the target was short (see Table 11), singleton presence and target type did not interact significantly [F(1,11) = 1.28, *MSE* = 896.75, p = .28].

Finally, as in all previous experiments (with the exception of Experiment 5, Chapter 3), there was no difference in RTs between singletons occurring before (*M* = 320 ms) versus after the target (*M* = 319 ms).

Table 11

Averages of subjects' mean RTs in ms (M) and mean error rates (%E), with standard errors (SE) for Experiment 11 as a function of singleton presence and target type

	Singleton condition						Effect size	
	Absent (A)			Present (P)			(P-A)	
Target	RT	SE	%E	RT	SE	%E	RT	%
Short	**300**	13	4	**310**	13	4	**10**	0
Long	**302**	16	4	**330**	20	7	**28**	3

Errors A two-way within-subjects error ANOVA with the factors of singleton presence (vs. absence) and target type (short vs. long duration) found a main effect of target type [F(1,11) = 5.69, *MSE* = .005, p < .05], indicating that subjects made fewer errors on trials where the target was short (*M* = 4%) than on trials where the target was long (*M* = 6%). This is consistent with earlier results (e.g. Experiments 9 and 10, Chapter 4) that have suggested that short targets might be easier to detect than long ones. Although there was no main effect of singleton presence on the error rates [F(1,11) = 1.28, *MSE* = .002, p = .28], there was a significant interaction between singleton presence and target type [F(1,11) = 6.14, *MSE* = .004, p < .05], revealing a trend towards an effect of singleton presence on trials where the target was long [t(11) = 1.81, p = .098] but no effect on trials where the target was short (see Table 11). Finally, there was no difference between singletons occurring before (*M* = 6%) versus after the target (*M* = 5%).

Overall, Experiment 11 has replicated the singleton interference effect found in all of the previous experiments. This replication demonstrates that the auditory AC demonstrated within this thesis, like visual AC (e.g. Theeuwes, 1992), can generalize to a task involving compound search, where the target-defining attribute does not also provide information about the necessary response.

The finding of interference here is also important, as it suggests that auditory AC occurs independently of the MMN and associated attentional orienting components. Because short and long length stimuli were intermixed at random in each sequence, there were no "standard" stimuli with which to contrast a deviant. Recall that a main requirement for elicitation of the MMN and associated attentional orienting components is that the deviant forms a change in a previously repetitive sequence of standard stimuli (see Näätänen, 1992, for review). As the sequences in the present experiment were never repetitive (because there were no "standard" stimuli)[12] it is unlikely that the irrelevant singleton would have produced a MMN at all. Yet singleton interference was still observed, suggesting that the interference effects found here are not simply behavioural correlates of the MMN (or an associated attentional orienting component). However, as I did not record ERPs these suggestions remain speculative. Indeed, ERP recording might provide and an interesting extension of the present experiments.

5.3 Experiment 12

Experiment 11 found a significant interference effect due to the presence of an irrelevant high intensity singleton. However, as anticipated from consideration of the new design used in that experiment (which might have encouraged feature search to some extent, and in which the target to singleton relative salience is likely to have been smaller than in previous experiments), numerical trends suggested that the interference effect was smaller than the effects previously found for high intensity singletons.

Nevertheless, although the design of Experiment 11 may have encouraged feature search, it did not explicitly prevent a singleton-detection strategy. By contrast, the target in the present experiment was prevented from being a reliable frequency singleton, making it impossible for subjects to perform the task using singleton detection mode. This should have forced subjects to adopt a feature-search mode in which they focus on the particular specified target feature. Subjects should therefore

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[12] Although the nontargets in the present experiment varied only on the dimension of duration, this should have been enough to prevent elicitation of the MMN, as the standard sounds used in the MMN studies are typically identical to one another (i.e. they do not vary on any dimension).

have been less open to distraction by the irrelevant singleton in the present experiment than in previous experiments where singleton detection mode was available (see Bacon & Egeth, 1994). If the reliable singleton effect found in Experiment 11 could be eliminated simply by manipulation of the search strategy available, this would indicate that auditory AC, like visual AC, depends on top-down strategies for attentional allocation.

As in Experiment 11, subjects searched for a pre-specified frequency target (480 Hz) that was present on each trial and responded according to its duration. However, in an important change from the previous experiment, the nontargets in the present experiment included tones of both higher (780 Hz) and lower frequencies (180 Hz). This should have prevented the use of singleton-detection mode as the target was no longer a reliable frequency singleton. If auditory AC, like visual AC, depends on subjects adopting a singleton detection strategy, then the presence (vs. absence) of the high intensity singleton should have no effect in this experiment (as subjects should adopt a feature based search and should therefore not be open to AC by the irrelevant singleton).

5.3.1 Method

Subjects & apparatus 12 new subjects took part in the experiment. Four were replaced due to near-chance level performance (50%, 50%, 49% and 44% error rates).

Stimuli & procedure The stimuli used were similar to those used in Experiment 11, except that nontargets and singletons were now of either high (780 Hz) or low frequency (180 Hz). Recall that nontargets and singletons in Experiment 11 were all of high frequency (780 Hz).

The design was similar to that of Experiment 11 except that nontargets and singletons could be of either high or low frequency. Frequencies were assigned at random with the following constraints: To ensure that the target was never a frequency singleton, each sequence contained at least one stimulus of high frequency and one of low frequency, as well as the medium frequency target. Volume singletons were just as likely to have high frequencies as they were to have low frequencies, and both types of singleton appeared before and after the target with equal probability.

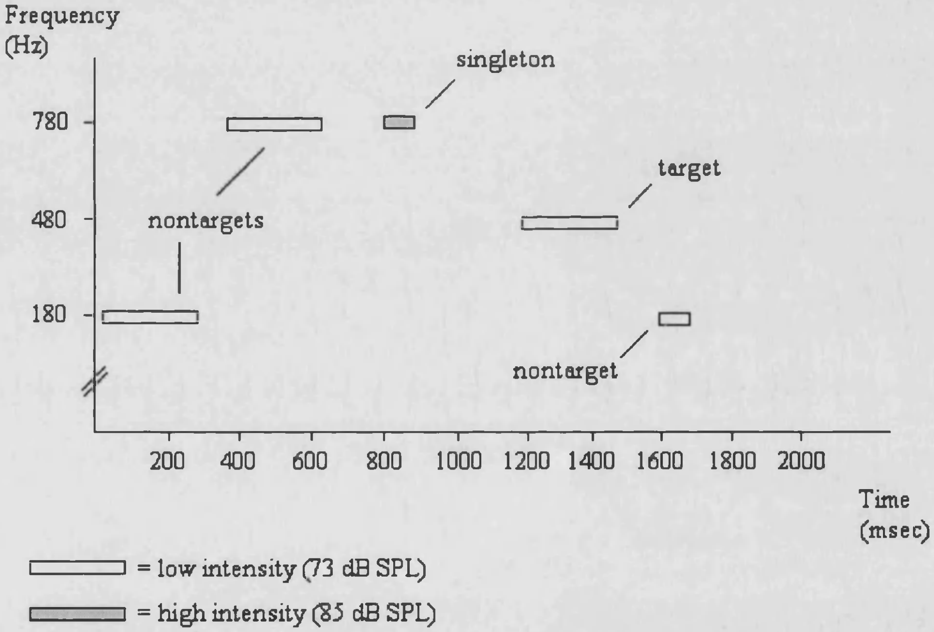

Figure 7: *schematic representation of an example trial from Experiment 12.*
Figure 7 shows a trial where the target was of long duration. The target was of short duration on the remaining 50%. Note however that the target had a frequency of 480 Hz in every trial. The figure shows an example of a trial where the singleton is present. This type of trial made up 50% of the total trials, as described in the method (section 5.3.1). On half of these singleton present trials the singleton was of short duration (as shown), whereas on the other half the singleton was of long duration. Similarly, the singleton was just as likely to appear at the lower frequency (as shown) as at the higher frequency. Finally, although the singleton is shown as appearing before the target, it was equally likely to appear after the target.

A 96 trial block included a fully-counterbalanced mix of the following factors and their combinations (in line with the constraints described above): target position, target duration (long or short), singleton presence, singleton position (before or after the target), singleton duration (long or short) and singleton frequency (high or low). Four experimental blocks were run, preceded by two practice blocks, each containing 16 trials.

5.3.2 Results and discussion

RTs Table 12 presents mean RTs and error rates across subjects as a function of singleton presence (vs. absence) and target type (short vs. long duration). A two-way within-subjects ANOVA using these factors found no significant effect of singleton presence (F < 1), indicating that responses were no different on target present trials (*M* = 365 ms) than on target absent trials (*M* = 368 ms). Thus for the first time in this thesis, a high intensity singleton failed to interfere with a task of detecting a frequency target. As in Experiment 11, there was no effect of target type (short vs. long) and no interaction between singleton presence and target type (F < 1 for both comparisons, see Table 12).

A potential account for the failure to find a significant singleton effect in the present experiment is that high intensity singletons might be less effective when presented at low frequencies than at high frequencies, so that when the effects of both are averaged (as in this experiment) a smaller singleton effect is produced than when all singletons are presented at high frequencies (in Experiment 11). However a one-way within-subjects ANOVA with the factor of singleton presence (vs. absence) using singleton-present data only from trials where singletons were of high frequency again found no significant effect of the presence (*M* = 373 ms) versus absence (*M* = 368 ms) of high frequency singletons (F < 1). This rules out the possibility that the addition of low frequency singletons had masked an interference effect by high frequency singletons.

Table 12

Averages of subjects' mean RTs in ms (M) and mean error rates (%E), with standard errors (SE) for Experiment 12 as a function of singleton presence and target type

	Singleton condition						Effect size	
	Absent (A)			Present (P)			(P-A)	
Target	RT	SE	%E	RT	SE	%E	RT	%
Long	**374**	33	13	**367**	27	14	**-7**	1
Short	**363**	31	10	**363**	31	14	**0**	4

A two-way mixed model ANOVA with the within-subjects factor of singleton presence (vs. absence) and the between-subjects factor of Experiment (11 vs. 12) found a significant interaction [F(1,22) = 5.36, *MSE* = 264.53, p < .05] such that the reliable singleton effect in Experiment 11 (mean interference effect = 19 ms) was eliminated in Experiment 12 (mean effect = -3 ms). This elimination in Experiment 12 of the singleton effect found in Experiment 11 is exactly as predicted from the hypothesis that auditory AC by irrelevant singletons depends on the subject's strategy for attentional allocation. Subjects in Experiment 11, as in previous experiments, were able to adopt a singleton-detection strategy because the targets themselves were reliable feature singletons, being presented among uniform high frequency nontargets. However, in Experiment 12, targets were presented among nontargets of both high and low frequency, ensuring that the targets were no longer feature singletons. This would have forced subjects to adopt a more specific search strategy, focusing on a single target feature rather than scanning the array for any singleton. The fact that singleton interference was eliminated under these circumstances provides further support for the idea that the singleton interference effects observed throughout this thesis depend on high-level attentional allocation to the singleton sound.

The between-experiment comparison also found a trend towards a main effect of experiment [F(1,22) = 3.05, p = .095] such that overall RTs were slower in the present experiment (*M* = 366 ms) than in Experiment 11 (*M* = 310 ms). Note that this difference was also apparent in the overall RTs for each experiment in the absence of the singleton (Experiment 11, *M* = 301 ms; Experiment 12, *M* = 368) and, to anticipate, this difference was also present in the error rates (Experiment 11, *M* = 5%; Experiment 12, *M* = 14%). This suggests that forcing subjects to adopt a feature-search strategy increased the overall difficulty of the task.

Finally, a further one-way within-subjects ANOVA carried out on data from singleton present trials with the factor of singleton position found no difference in the effects of singletons occurring before (*M* = 367 ms) versus after the target (*M* = 363 ms, F < 1).

Errors A two-way within-subjects ANOVA on the error rates with the factors of singleton presence (vs. absence) and target type (short vs. long duration) revealed no main effect of target type, and neither did target type interact significantly with singleton presence (p > .15 in both comparisons). However, there was a small effect of singleton presence which reached significance [F(1,11) = 7.99, *MSE* = .004, p < .05], indicating that subjects made 2% more errors when the singleton was present (*M* =

14%) than when it was absent (*M* = 12%). This could reflect a trade-off between RTs and error rates, such that the singleton effect in this experiment simply appears in the error rates (whereas in Experiment 11 it had appeared in the RTs). However, a two-way mixed model ANOVA using the within-subjects factor of singleton presence (vs. absence) and the between-subjects factor of Experiment (11 vs. 12) found no significant difference between the singleton effect in the present experiment (*M* = 2%) and that of Experiment 11 (*M* = 1%), F < 1. Recall that by contrast, the singleton effect in the RTs was significantly reduced in the present experiment compared with Experiment 11. Thus overall Experiment 12 shows a reduced singleton cost compared with Experiment 11.

A further one-way within-subjects ANOVA carried out on data from singleton present trials with the factor of singleton position found no difference in the effects of singletons occurring before (*M* = 14%) versus after the target (*M* = 13%, F< 1).

Overall, the fact that the AC effect due to high intensity singletons (which is usually very robust, perhaps because of their high salience) can be eliminated simply by manipulating the search strategy available is important in providing additional evidence that the singleton effects found within all the experiments in this thesis relate to the higher-level process of attentional capture, rather than to some lower-level perceptual factors that might cause interference or facilitation.

5.4 Chapter discussion

Experiments 11 and 12 have demonstrated that auditory AC can be reduced when the search task is changed very slightly so that it cannot be carried out using a singleton detection strategy. This finding provides further evidence that singleton interference effects relate to processes involved with attentional allocation, as these effects are reduced in situations where attention is no longer allocated towards the irrelevant singleton feature. It also provides an interesting parallel with the visual version of the effect, in demonstrating that auditory and visual AC both depend on subjects' attentional allocation strategies (see Bacon & Egeth, 1994).

Note however that the findings could also be explained in terms of the interference effect being eliminated due to higher perceptual load in Experiment 12 than Experiment 11 (recall that overall responses were slower and less accurate in Experiment 12 than in Experiment 11). There is much evidence to suggest that irrelevant distractors are rejected more efficiently if the task at hand is of high rather than low perceptual load (e.g. Lavie, 1995; see Lavie, 2000 for review). This is typically attributed to target processing under high load occupying the subject's full attention, leaving little or no attention available for processing of irrelevant distractors. Thus it is possible that the interference effect from Experiment 11 was eliminated in Experiment 12 because the task was of higher perceptual load, rather than because of the change in search strategy. Indeed, in their equivalent visual experiment, Bacon and Egeth (1994, Experiment 3) found an effect of perceptual load, such that RTs were slower when the target was not a form singleton (approximate $M = 620$ ms) than when it was (approximate *M* = 595 ms). However, in both a search strategy account and a perceptual load account singleton interference is prevented when attention is withdrawn from the singleton items. Thus both accounts support the idea that singleton interference is due to the singleton capturing attention away from the target, and thus provide further support for an AC account of singleton effects when these are found (e.g. in Experiment 11).

Chapter 6

Effects of irrelevant visual singletons on target discrimination in visual sequential search

6.1 Introduction

The experiments described so far have found converging evidence for AC by irrelevant auditory singletons in auditory search sequences. The fact that these studies have found auditory AC using temporal search arrays also provides evidence that attention can be captured to an object that is differentiated from other objects in terms of temporal position rather than spatial location. The experiments described within this chapter are designed to ask whether a similar temporal AC effect can be found in the visual domain, i.e. whether the presence of an irrelevant visual singleton (e.g. a red nontarget among black) in a sequential search task similar to the tasks used in previous auditory experiments will capture attention from a target task based on another dimension (e.g. size).

As described in the general introduction (Chapter 1), research into visual AC has until recently used visual search arrays in which all stimuli are presented at the same time in different spatial locations. However one previous study has examined visual AC in a task where all stimuli were presented at fixation, one after another in a fast sequence (using rapid serial visual presentation, RSVP). Folk, Leber and Egeth (2002) asked subjects to identify a probe letter by its colour and report its identity. On some trials, one of the central letters was surrounded by four peripheral distractor symbols, in the form of number signs (#). These distractor symbols occupied one of four temporal positions relative to the target: they could surround the letter that appeared directly before the target (lag 1); the letter that appeared two items before the target (lag 2); the target letter itself (lag 0); or the letter that appeared directly after the target (lag -1). On 25% of trials these distractor symbols were absent. On a further 25% of trials all four distractor symbols were grey (the same colour as the nontargets). On another 25% of trials one of the symbols was presented in the same colour as the target, while the rest were grey. And on the final 25% of the trials one of the symbols was presented in a colour that was different to the target, with the rest of the symbols grey. Both colour singleton distractors produced a significant cost to target identification accuracy compared with the all-grey and no-distractor conditions (but only when they appeared before the target letter, at lags 1 or 2). However, when singleton-detection mode was prevented (by including nontargets of several different colours), the distractors only captured attention if they were of the same colour as the target. This is similar to the findings of Bacon and Egeth (1994) and the results described here in Chapter 5, in suggesting that AC by irrelevant items can be prevented when subjects adopt a focused, feature search strategy.

The results of Folk et al. (2002) thus establish spatial AC by an irrelevant singleton distractor presented in a peripheral display that surrounds one of the nontarget items in an RSVP search task. However the purpose of the experiments described within this chapter was to examine whether one of the nontargets could itself capture attention when it was presented with a singleton feature. In other words, Folk et al. (2002) added a spatial distractor array to one of the RSVP frames, in which one of the items could be a colour singleton. By contrast, the idea behind the present experiments was to test whether an irrelevant singleton *within* the RSVP sequence could capture attention. Were such AC to be found, it would of course be nonspatial, as all RSVP items are presented in the centre of the screen. In this way, the visual experiments presented here provide a direct analogue for the auditory experiments presented in Chapters 3 to 5.

The possibility of AC by one of the nontarget items in RSVP search has not yet been tested. However some indirect implications may be drawn from the "attentional blink" paradigm. The term "attentional blink" refers to the finding that subjects fail to detect the second of two targets in an RSVP stream (referred to as the 'probe') when it is presented within 500 ms of the first (referred to as the 'target'). Performance in trials in which subjects must both identify the target letter (typically partially-specified as being of a certain colour) and report the presence or absence of the probe (typically specified as a particular letter) is compared with performance in trials where subjects are asked to ignore the target and must only detect the probe. The typical finding is that probe detection is significantly impaired when the task involves responding to (rather than ignoring) the preceding target, as long as the probe occurs within 500 ms of the target (e.g. Broadbent & Broadbent, 1987; Raymond, Shapiro & Arnell, 1992). This finding suggests that, once attention is allocated towards the target item, there is a certain period of time throughout which it is not available for re-allocation towards the subsequent probe. This fits well with the present demonstrations of AC in rapid serial auditory arrays, as it suggests that visual items can also capture attention in serial search arrays.

However, even though the targets in the attentional blink experiments are typically defined as colour singletons, these studies focus on the ability of an *attended target* to capture attention and as such do not relate directly to the AC research (which examines the ability of an *irrelevant singleton* to capture attention). In fact, the condition in which subjects are asked to ignore the singleton target is more relevant to the present question. However, as the attentional blink experiments do not include a condition in which the colour singleton target is absent, there is no baseline against which to test whether this supposedly ignored singleton may have captured attention and interfered with performance. The present experiments were designed to ask whether an irrelevant visual singleton in a RSVP search task could capture attention in the same way as auditory singletons in RSAP search tasks.

6.2 Experiment 13

Subjects searched a visual sequence of five letters (all Ns) for targets that were defined by size. As in previous auditory discrimination experiments (Chapters 3-5) a target was present on each trial. Subjects responded according to whether the target was large or small. On 50% of trials an irrelevant feature singleton was presented. This item was the same size as the nontargets but of a different colour. As in the auditory experiments reported previously, the hypothesis that the singletons in such a design should capture attention would predict interference to target responses on singleton present trials compared with singleton absent trials.

6.2.1 Method

Subjects Eight new subjects were run on this experiment.

Apparatus and stimuli The experiment was created and run on a PC using E-Prime (version 1.1), sold by Psychology Software Tools Inc. Visual stimuli, all of which had the form of an uppercase letter N, appeared one after another in the centre of the screen. At a viewing distance of 60cm, nontargets and singletons subtended a visual angle of 1.4° vertically and horizontally. Large targets subtended a visual angle of 1.7° vertically and horizontally and small targets subtended a visual angle of 1.1° vertically and horizontally. Letters were presented against a white background. For half the subjects, nontargets and targets were black in colour, and singletons were red. For the other half, nontargets and targets were red and singletons were black.

Design & Procedure As in the auditory discrimination experiments (Chapters 3-5) targets appeared on every trial in either the third or fourth position with equal probability. Targets were equally likely to be large or small. Also as in previous experiments, irrelevant distractor singletons appeared on 50% of trials, directly before or after the target with equal probability. Each sequence started with a black fixation cross presented at the centre of the screen for 500 ms. This was followed by a 50 ms blank screen, after which the first item in the sequence was presented. Each of the five items in the sequence remained on screen for 70 ms and was followed by a 70 ms blank screen. (Note that the stimulus durations used here are shorter than those used in the auditory experiments, as pilot testing had shown that the visual task was too easy to reveal attentional effects when slower stimulus durations were used). After presentation of the last item in the sequence, a question mark was presented at the centre of the screen. Subjects were requested to respond with a key press: “1” for “large target” or “2” for “small target”, using the index and middle fingers of the right hand respectively, upon presentation of this question mark. As in previous experiments, 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.

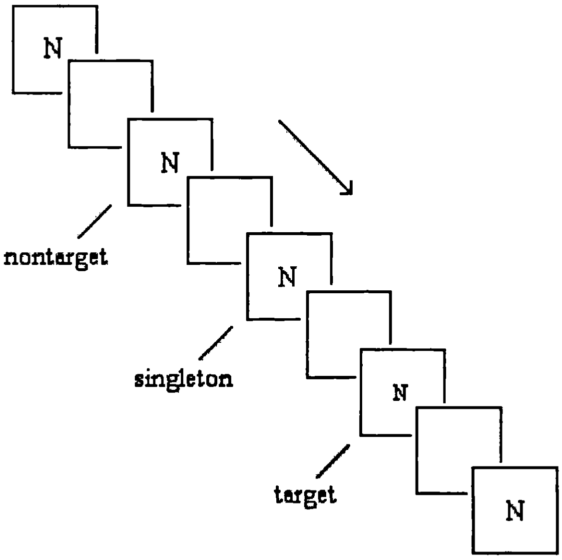

Figure 8: *schematic representation of an example trial from Experiment 13*

Figure 8 shows an example of a trial where the target is smaller than the nontargets. The target was larger than nontargets on the remaining 50% of trials. As in previous experiments, the singleton was only present on 50% of the total trials, as described in the method (section 6.2.1).

Subjects were instructed that a target would be present on every trial. They were asked to focus on the sizes of the stimuli and ignore any variation in other dimensions. They were informed that some distractor items of a different colour from the targets and nontargets would occur and were warned that their performance might be harmed if they failed to ignore these distractors. A short practice block of 16 trials preceded two experimental blocks, each containing 80 trials.[13] The total run-time for this experiment and Experiment 14 was 10-15 minutes.

6.2.2 Results and discussion

RTs Preliminary analysis indicated that singleton colour (red in black streams vs. black in red streams) did not interact with the factor of singleton presence (vs. absence) and the data is thus pooled across singleton colour. Table 13 presents mean RTs and error rates across subjects as a function of singleton presence (vs. absence) and target type (large vs. small). A two-way within-subjects ANOVA using these factors revealed a significant main effect of singleton presence [F(1,7) = 7.40, *MSE* = 14573.09, p < .05]. As in the previous auditory experiments, target RTs were slower on singleton present trials (*M* = 426 ms) than on singleton absent trials (*M* = 384 ms), suggesting that the colour singleton may have captured attention despite being irrelevant to the task. There was also a main effect of target type indicating that responses were faster when the target was large (*M* = 377 ms) than when it was small (*M* = 433 ms). This is likely to be due to the fact that a large visual target appearing in a stream of smaller items occupies some new areas of the display that the smaller items have not previously occupied, producing a type of abrupt-onset in those areas. By contrast a small visual target in a stream of larger items does not occupy any new area of space and so does not produce any abrupt-onset. As such the small target is likely to be harder to detect than the large one. This finding is similar to demonstrations of search asymmetries within spatial visual search arrays. In particular, there is evidence that items with

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[13] Although the auditory experiments used six blocks of around 96 trials, pilot testing of the visual task confirmed that the AC effect could be found in the first two blocks.

"more" of a particular feature are often identified faster than those with "less" of that feature. For example, search for long lines among short is more efficient than search for short lines among long (Treisman & Gormican, 1988).

Although there was a numerical trend for a larger singleton effect on trials where the target was small than on trials where it was large (see Table 13), the factors of singleton presence and target type did not interact significantly (F(1,7) = 1.98, *MSE* = 1979.31, p = .202). Note however, that the trend appears to be consistent with the findings of Chapters 4 and 5, in suggesting that the singleton effect tends to be stronger for the target that is harder to identify (as shown by the main effect of target type). This may have been due to greater relative salience of the singleton versus the target (i.e. targets that are harder to detect are relatively less salient than the singleton by comparison with targets that are easier to detect).

A further one-way within-subjects ANOVA on data from singleton present trials using the factor of singleton position (before vs. after the target) revealed a significant effect, such that responses were slower when the singleton occurred before (*M* = 449 ms) versus after the target [*M* = 400 ms, F(1,7) = 9.01, *MSE* = 9381.38, p < .05]. Indeed, RTs when the singleton occurred after the target were not significantly different from RTs when the singleton was absent (*M* = 383 ms, t(7) = 1.14, p = .29). This result is similar to the finding of Folk, Leber and Egeth (2002) that an irrelevant colour singleton in an array of irrelevant distractors only captured attention if this array appeared before rather than after the target. A similar pattern of greater interference for singletons appearing before (vs. after) the target was also found in previous auditory experiments (Chapters 3-5), although this effect was normally found in the error rates rather than the RTs (with the exception of Experiment 5, Chapter 3).

Table 13

Averages of subjects' mean RTs in ms (RT) and mean error rates (%E), with standard errors (SE) for Experiment 13 as a function of singleton presence and target type

	Singleton presence						Effect size	
	Absent (A)			Present (P)			(P-A)	
Target	RT	SE	%E	RT	SE	%E	RT	%
Large	**363**	30	7	**390**	37	8	**27**	1
Small	**404**	48	10	**462**	45	11	**58**	1

Errors The two-way error ANOVA with the factors of singleton presence and target type revealed no significant main effects or interactions (p > .20 for all comparisons). Note, however, that the error rates showed similar trends to the RTs. In particular, error rates were 1% greater in the presence (vs. absence) of the singleton and subjects made more errors when the target was small (*M* = 11%) than when it was large (*M* = 8%). This supports the RT results in suggesting that the small target might have been harder to detect than the large target.

In line with the RT results, a further one-way within-subjects ANOVA on error data from singleton present trials using the factor of singleton position (before vs. after the target) revealed a trend suggesting that subjects made more errors when the singleton occurred before (*M* = 11%) versus after the target [*M* = 8%, F(1,7) = 4.94, *MSE* = 36.00, p = .062]. Error rates in the latter condition were very similar to error rates when the singleton was absent (*M* = 9%). Thus, as was found in the RTs of the present experiment and in the auditory experiments reported earlier (Chapters 3-5), the irrelevant colour singleton appears to cause more interference when it appears before rather than after the target. As mentioned in relation to the RT results, this finding is consistent with the results of Folk et al. (2002) who found AC by singletons in arrays appearing before rather than after the target. As mentioned earlier, it is likely that the appearance of a singleton before the target is more damaging to target processing than the appearance of a singleton after the target (by which time some target processing will have occurred without competition).

In conclusion, the present experiment has found significant interference due to the presence of an irrelevant colour singleton in an RSVP discrimination task. This finding is suggestive of AC by the irrelevant singleton.

6.3 Experiment 14

I have argued that the interference effect found in Experiment 13 is likely to be due to AC by the irrelevant colour singleton. Experiment 14 was designed to confirm that this interference was due to the presence of a colour singleton in the search stream, rather than being due to a lower-level effect associated with the introduction of a differently-coloured item to the search array. For example, it is possible that the singleton interference observed in Experiment 13 might have been due to contrast effects. Recall that the singleton in Experiment 13 always appeared either directly before or after the target. Thus the interference effect observed in that experiment could have been a result of it being easier to compare the target with a nontarget (of the same colour) than with a singleton (of a different colour). The present experiment was designed to rule out such potential low-level effects and thus strengthen the claim that the interference (and the AC that it reflects) were due to the irrelevant distractor being singleton stimulus, rather than it being different in colour from the other nontargets.

Subjects carried out the size discrimination task used in Experiment 13. On 50% of trials, stimuli were all the same colour. On the remaining 50% of trials, stimuli alternated between the target colour and a distractor colour. These colour alternation trials should reveal any contrast effects, as the target was presented in between two items of a different colour. If the interference effects seen in Experiment 13 are due to contrast effects, they should persist in the alternation condition, as subjects will not be able to compare the target with any item of the same colour. By contrast, if the interference effects are due to AC by the presence of a unique colour singleton, they should be eliminated in the alternation condition.

6.3.1 Method

Subjects Eight new subjects were run on this experiment.

Apparatus and stimuli The equipment used was the same as described for Experiment 1. Stimulus sizes were as described for Experiment 13. For half the subjects, targets and nontargets were black in colour and distractors were red. For the other half, targets and nontargets were red and distractors were black.

Design & Procedure On 50% of the trials, sequences were made up only of nontargets and targets so that each sequence was presented in the target colour only. On the remaining 50% of trials, the letters alternated in colour between the target colour and the irrelevant distractor colour. Alternating sequences were just as likely to start with the distractor colour as with the target colour. In order to avoid any contingency between the colour of the first letter in the sequence and subsequent target position, sequences consisted of either six or seven letters, with equal probability. Targets were equally likely to be large or small and they appeared on every trial in the fourth or fifth position (with equal probability) of the six-letter sequences and in the fifth or sixth position (with equal probability) of the seven-letter sequences. Subjects were told that sequences would consist of letters that were either all presented in the same colour or presented in alternating colours. They were informed of the target colour and were aware that targets would never be presented in the distractor colour. Overall they were asked to ignore any colour variation and warned that their performance might be harmed if they failed to do so. All other aspects of the design and procedure were the same as in Experiment 13.

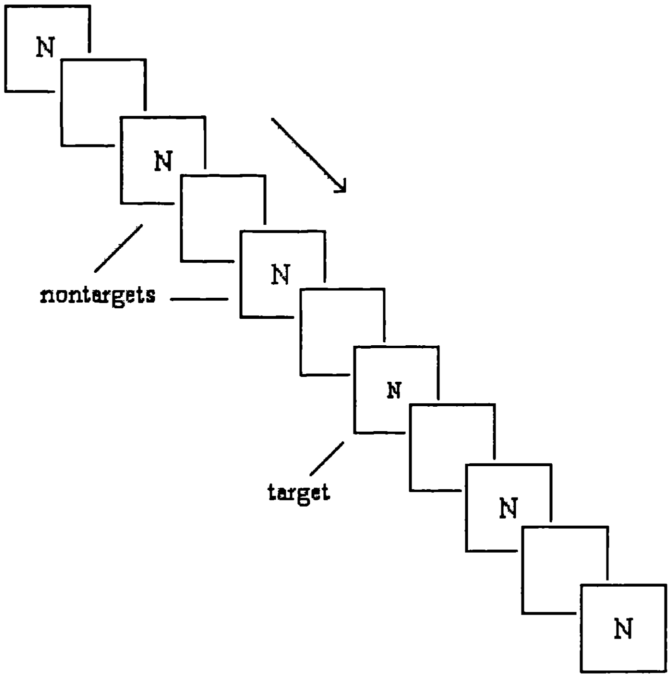

Figure 9: *schematic representation of an example trial from Experiment 14*
Figure 9 shows an example of a trial where the target is smaller than the nontargets. On 50% of trials the target was larger). Note also that the figure shows a sequence containing six letters, but sequences were just as likely to contain seven letters for reasons discussed in the method (section 6.3.1). Finally, the colour alternation shown here was only present on 50% of the total trials.

6.3.2 Results and discussion

RTs As in Experiment 13, target colour (black vs. red) did not interact with the presence/absence of alternation, and the data are thus pooled across the different colour conditions. Table 14 presents mean RTs and error rates across subjects as a function of alternation condition (alternation absent vs. present) and target type (large vs. small). In a two-way within-subjects ANOVA using these factors there were no significant main effects or interactions ($p > .20$ for all comparisons). Note however that there was a numerical trend for faster responses to large targets than to small targets, as in Experiment 13. It is especially important that there was no main effect of the presence ($M = 290$ ms) versus absence ($M = 292$ ms) of the colour alternation [$F(1,7) = .047$, $MSE = 26.74$, $p = .83$]. Moreover, a one-way ANOVA comparison of the effects of singleton presence in Experiment 13 and alternation presence in Experiment 14 found a significant interaction [$F(1,14) = 5.17$, $MSE = 3211.61$, $p = .039$], confirming that the singleton effect in Experiment 13 ($M = 42$ ms) was significantly stronger than the effects of colour alternation in Experiment 14 ($M = -2$ ms). Thus the singleton interference effects of Experiment 13 depend on the presence of a single unique item and cannot be explained in terms of the simple presence of another colour in the search display.

This between-experiment ANOVA also found a significant main effect of experiment, such that RTs were faster in the present experiment ($M = 286$ ms) than in Experiment 13 ($M = 402$ ms, $F(1,14) = 10.12$, $p < .01$). As can be seen in Tables 14 and 15, this effect was found in the absence as well as the presence of the singleton or colour alteration. This may be because the present experiment used stimulus sequences of six or seven items, whereas Experiment 13 used sequences of five items. Although the "extra" items in the present experiment were presented at the beginning of the sequences (so that the time in between the appearance of the target and the response window was the same in both experiments), it is possible that the longer sequences used here allowed subjects to prepare more effectively for the subsequent target presentation, leading to faster target RTs. In any case, note that this finding does not bear on the critical aspect of the results presented here, i.e. that the strong interference effect found due to the presence of a unique colour singleton in Experiment 13 was not found when the singleton was replaced by colour alternation.

Table 14

Averages of subjects' mean RTs in ms (RT) and mean error rates (%E), with standard errors (SE) for Experiment 14 as a function of alternation condition and target type

	Alternation condition						Effect size	
	Absent (A)			Present (P)			(P-A)	
Target	RT	SE	%E	RT	SE	%E	RT	%
Large	**282**	27	3	**278**	29	1	**-4**	-2
Small	**298**	28	2	**306**	41	2	**8**	0

Errors Overall there were a small number of errors in this experiment (*M* = 2%), and not much variation in errors between experimental conditions. A two-way within-subjects error ANOVA with the factors of alternation condition and target type showed no main effect of either factor (p > .20 for both comparisons). The interaction between alternation presence and target type was not significant [F(1,7)=3.38, *MSE* = 9.03, p = .11] and note that any trend towards a higher error rate for large targets in the absence (vs. presence) of the alternation (see Table 14) is in the opposite direction to the singleton interference effect. In any case this trend towards a facilitatory effect of alternation on trials where the target was large was not itself significant [t(7) = 1.70, p = .13].

Overall, this experiment has shown that colour alternation in the visual search sequences does not produce reliable interference. This suggests that the interference effect found in Experiment 13 is likely to have been due to the presence of a unique colour singleton, rather than simply to lower-level factors associated with the presence of a second colour in the search array.

6.4 Chapter discussion

The two experiments presented within this chapter together suggest that irrelevant visual singletons can capture attention in a temporal visual search task. Experiment 13 found significant interference in RTs due to the presence of an irrelevant colour singleton in an RSVP discrimination task. Experiment 14 provided further evidence in support of an AC explanation by ruling out the possibility that the interference effect was due to lower-level effects associated with the presence of a second colour in the search array.

These results have implications for previous RSVP studies of visual AC. Recall that Folk, Leber and Egeth (2002) demonstrated spatial visual AC by irrelevant singleton distractors that flank the central search stimuli. The present experiments extend these findings to show a nonspatial interference effect from one of the nontargets in the central stream, appearing either before or after the target (although, as in Folk et al., 2002, most of the interference effect was due to singletons that appeared before the target). These results support the findings of Folk et al. (2002) in suggesting that visual AC can occur even when the target's spatial location is certain, as long as there is some other uncertainty over target appearance (in this case, the target's temporal location is uncertain) so that subjects are still required to carry out some sort of search (cf. Theeuwes, 1991b; Yantis & Jonides, 1990).

Interestingly, the nonspatial effect demonstrated here did not depend on subjects adopting an attentional set for the particular singleton colour (as targets and singletons were different colours, and in fact targets were defined by size and not by colour at all). This raises the intriguing possibility that the differences between the spatial and nonspatial RSVP effects might be similar to the differences in the spatial and nonspatial AC effects described within the spatial cuing and visual search paradigms. Recall that Folk and Remington (1998) suggested that there might be two different types of visual AC: a spatial effect that was more open to top-down influences and thus often depended on the target and singleton sharing the same defining feature (e.g. Folk, Remington and Johnston, 1992); and a nonspatial effect that was less open to top-down control and tended to persist despite targets and singletons being defined by very different features (e.g. Theeuwes, 1992). As the effect observed within this chapter is by definition a nonspatial effect, it is particularly interesting that it was present despite targets and singletons being defined on different dimensions (recall that the effect in Folk, Leber and Egeth's, 2002, study depended on singletons and targets both being defined by colour). Thus the present results provide a hint that similar processes may be involved in this RSVP version of the AC phenomenon as in the more traditional visual search or spatial cuing versions.

Taken together, the visual results presented here and the findings of Folk et al. (2002) agree with previous research in suggesting that the visual system is tuned to detecting items that are unique against the background stimulation yet irrelevant to an ongoing task. Although many previous studies have demonstrated that irrelevant singletons could capture visual attention in this way if they appeared as part of a single spatial array (or as cues appearing immediately before a search task), these are the first demonstrations of visual AC by objects that are differentiated from other objects in time rather than in space. As such, the present findings suggest that the visual attentional system, like the auditory system, can be tuned to detect changes in ongoing stimulation (rather than simply detecting discontinuities in static, spatial displays, as has been shown by previous visual search studies of attention).

The findings of this chapter also have implications for the attentional blink research, as they suggest that the "targets" in the attentional blink design can capture attention even when they are ignored. This possibility had not previously been tested within the attentional blink paradigm, which had focused on the effects of *attended* targets on attentional allocation. However, it is interesting that the interference effect found here was observed in the RT data but not in the error rates (although note that the numerical trends in the error rates were in the direction of singleton interference). This is in contrast to the attentional blink findings, which are usually presented in terms of error rates rather than RTs.

Chapter 7

General Discussion

7.1 Overview of findings and their implications for previous research

The experiments described within this thesis have found significant behavioural costs in auditory search tasks due to the presence of an irrelevant auditory feature singleton. This finding has generalised 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 (Chapter 2) as well as tasks involving discrimination between two targets, one of which is always present (Chapter 3). This consistent generalisation across different types of singleton and across different tasks indicates that the singleton interference effect is associated with the presence of a unique yet irrelevant feature singleton, in line with the hypothesis that the singleton interference found is due to capture of attention and as such is not confined to any particular combinations of singleton and target, or to any lower-level factor associated with singleton presence (as such lower-level factors would be expected to vary across different types of singletons and different search tasks).

In addition, as singleton interference was found in all the experiments irrespective of the particular combination of target and singleton features (with the exception of the combination of high intensity singletons and high frequency targets in the discrimination task, but not the detection task), this thesis does not find evidence for a specific role of relative salience of the singleton feature compared with the target feature. This is in contrast to the visual AC research that has suggested that the relative salience of the targets and singletons can be important determinants of visual AC (for review see Theeuwes, 1994a). 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. However the data presented here speak only indirectly to this issue, as the salience of singleton and target features was not systematically varied. This might be an interesting topic for further investigation. For example, it would be useful to examine whether, like visual AC (e.g. Theeuwes, 1992, Experiment 2), auditory AC can be eliminated when the singleton item is made much less salient than the target item (by using small feature differences between singletons and nontargets and large feature differences between targets and nontargets).

Chapter 4 showed that, although the irrelevant singleton feature leads to consistent interference when it is presented within a nontarget sound, it causes facilitation when presented within the target sound (Experiment 9). Thus the very same singleton feature can, depending on the object in which it is presented, cause interference in one trial and facilitation in another. This finding provides further evidence that singleton interference effects are due to allocation of attention towards the singleton feature, as this would be expected to lead to facilitation when the singleton feature appears in a target sound (and attention is therefore allocated towards the relevant target sound), but to interference when the singleton feature appears in a nontarget sound (and attention is therefore allocated to an irrelevant sound).

The facilitation effect shown in Chapter 4 is also important in its contrast with previous demonstrations of expectancy effects in auditory attention. A typical expectancy finding is that judgements made on stimuli presented at unexpected frequencies are impaired relative to judgements on stimuli at expected frequencies (e.g. Mori & Ward, 1991; Mondor, Zattore & Terrio, 1998). However the facilitation observed in Chapter 4 goes against these effects of expectancy, as the targets are twice as likely to appear at the non-singleton frequency than at the singleton frequency, yet judgements on targets with the unexpected singleton frequency are faster and more accurate than judgements on targets with the more expected non-singleton frequency. Thus auditory AC by an irrelevant singleton appears to be strong enough to override expectancy effects, presumably because it provides an efficient means of re-focusing attention on the singleton object regardless of expectancy.

Chapter 4 also demonstrated that singleton interference could persist when the target and the singleton were separated by another sound (Experiment 10). This ruled out explanations for singleton interference in terms of lower-level interactions between adjacent sounds, such as masking, as any such interactions would have been eliminated when the target and singleton were separated by an intervening sound. The findings of Experiment 10 also suggested that auditory AC can persist despite a singleton-target separation of 270 ms in which another object is presented.

The finding that singleton interference can persist across an intervening nontarget is similar to the demonstration by Folk et al. (2002) that the spatial visual AC effect they found within an RSVP task also persisted when a nontarget stimulus separated the singleton from the target. However, in contrast to Folk et al.'s (2002) experiments (where interference was only caused by singletons that appeared before rather than after the target), Experiment 10 found interference on RTs from singletons appearing both before and after the target. Indeed, this pattern was found throughout the auditory experiments in the present thesis. This consistent finding of a cost to RTs from singletons occurring after, as well as before, target presentation is likely to be due to the design of the auditory tasks used here. As responses were given at the end of each stream, it is possible that target search was exhaustive, terminating only at the end of the stream. In this case the singleton stimulus would have been processed wherever it occurred in the stream. Note however that error rates in the present experiments were typically higher when the singleton occurred before rather than after the target. This may be because AC is more likely to disrupt target perception when the singleton occurs before the target, whereas when the singleton occurs after the target early perceptual processing of the target can progress without competition.

Chapter 5 presented evidence that auditory AC depends on subjects using a singleton detection strategy in their allocation of attention (i.e. directing attention towards any unique singleton item in the array). Experiment 12 prevented this strategy by making the nontargets heterogeneous so that the target was no longer a feature singleton and a singleton detection strategy would thus no longer be useful in identifying the target. Subjects would then have been forced into a feature-based search, in which attention would have been allocated only towards the item with the particular target feature. Under these circumstances, auditory AC was eliminated. The fact that the reliable singleton interference effect found in the previous experiments can be modulated by a change in top-down strategies for attentional allocation provides further evidence that this singleton interference reflects capture of attention (and as such is eliminated when attention is no longer allocated towards the singleton). This finding also demonstrates that auditory AC, like visual AC, is not purely stimulus-driven, but instead depends on top-down factors as well.

Overall, the auditory findings described in Chapters 2-5 are best explained in terms of AC by the singleton sound and converge to provide a demonstration of AC in the auditory domain. Previous research had established that auditory attention could 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; Nosofsky, 1983; Schröger and Wolff, 1998; Scharf et al., 1987; Yama & Robinson, 1982). However, the present results have shown that such focused auditory attention can be interrupted by the presence of a unique singleton distractor.

Because the present studies provide the first demonstration of AC in hearing, the experimental evidence is not yet sufficient to support a model of the processes that might underlie the phenomenon. Such a model will be necessary in the future, however, to explain exactly what constitutes AC within the auditory search tasks used within this thesis. It seems possible that a model of auditory AC might relate to models of AC within the visual domain. For example, recall that Theeuwes (1991a, 1992, 1994) suggested a model of visual AC based on the relative salience of targets and singletons. According to this model, feature dimensions are analysed separately, allowing pre-attentive identification of areas where large feature differences occur between items (e.g. a green item among red will produce a large feature difference on a colour map whereas a lighter red item among darker red items will produce a small feature difference). Attention is then directed first towards items that produce the largest feature differences, leading to AC by any irrelevant singleton items that produce larger featural differences than the target. This model could also accommodate the present findings of auditory AC, with the assumption that subjects treated the short, rapidly-presented auditory streams as single search arrays. This assumption seems likely, given the fact that short-term echoic memory lasts for around two seconds (Darwin, Turvey & Crowder, 1972), which would allow the sounds making up each sequence in the present experiments to be stored in a single buffer for simultaneous analysis. Indeed, the fact that there were no effects of singleton position (before vs. after the target) on RTs (the main performance measure) also supports the idea that the arrays were processed as a whole, rather than item-by-item. Given this assumption, it could then be proposed (in line with Theeuwes's model) that auditory attention is simply drawn towards whichever items in the array produce the largest differences on preattentively-determined auditory feature maps, leading to AC by singleton items if they produce larger feature differences than targets. This characterisation remains speculative, but further development and experimental investigation of a tentative model along these lines might be a potentially interesting area for future research.

The present demonstration of auditory AC provides further evidence for the view that one function of hearing might be to act as an early warning system, scanning the environment for changes in all directions while the other senses typically focus on more restricted areas of space (e.g. touch is restricted to areas of space very near the body, and vision, while it can take in a very large area of space, is restricted in the directions it can cover, e.g. we cannot see behind us). Previous evidence to support the idea that the auditory system might be tuned to detect changes had come either from responses to single auditory stimuli in an otherwise empty background (e.g. the orienting response; Pumphrey, 1950; Sokolov, 1963) or from responses in situations where there was not much demand on auditory attention (because slow presentation rates were used, as in the typical MMN research) and where the deviant distractors used were not irrelevant to the task as they either predicted the target sound (e.g. Schröger, 1996) or were contained within the target sound (e.g. Schröger & Wolff, 1998). In contrast, the present research demonstrates that auditory stimuli can capture attention even within a demanding auditory task, and despite being defined on an irrelevant dimension, simply by virtue of being unique against a homogeneous auditory background (as long as the target is unique as well).

The present demonstration of auditory AC is different from previous visual search demonstrations of AC in that the auditory tasks described here used sequential presentation of stimuli whereas the visual tasks used spatial search arrays. This change to the task was essential simply because of the different ways in which early sensory information is processed in the different modalities. Whereas the visual system prioritizes the spatial location of incoming stimulation, the auditory system processes spatial location with lower priority than other stimulus attributes such as frequency (e.g. Kubovy, 1981, Merzenich, Colwell & Andersen, 1982; Woods et al., 2001). For this reason, most previous research into focused auditory attention and the effects of auditory distractors has used temporal rather than spatial search arrays.

However, as the sequential search task did not provide a direct auditory analogue for the previous visual search AC tasks, Chapter 6 presented two final experiments demonstrating effects of visual AC in a task that was very similar to the tasks used in the auditory AC experiments. These experiments confirmed that visual singletons could also produce interference in a size discrimination task in which the stimuli were presented within a RSVP stream (Experiment 13, Chapter 6). This interference cannot be explained in terms of lower-level factors associated with the presence of a second colour in the display (e.g. contrast effects), as removing its uniqueness by including an alternation in the display items between the target colour and a second colour does not lead to an interference effect (Experiment 14). Thus the effect depends on the presence of a unique yet irrelevant colour singleton. Overall Chapter 6 demonstrated a nonspatial AC effect due to irrelevant colour singletons in RSVP search that is comparable to the auditory AC effect demonstrated in the previous experiments.

7.2 Commonalities between attentional processes in vision and hearing

Although the present auditory experiments used a sequential task that was very different from the typical visual search AC tasks, they nevertheless identified several characteristics of auditory AC that appear very similar to those of visual AC. For example, the present findings of singleton interference, although they do not indicate spatial interference effects, are still consistent with previous visual search studies that have demonstrated behavioural costs associated with AC by an irrelevant singleton feature that is presented within a nontarget sound (e.g. Pashler, 1988; Theeuwes, 1992). In addition, the demonstration in this thesis of facilitation due to an irrelevant auditory feature singleton that is presented within the target sound (Experiment 9, Chapter 4) appears similar to previous demonstrations of facilitation due to visual AC (e.g. Jonides & Yantis, 1988). Note however that an additional advantage of Experiment 9 is that it demonstrates interference and facilitation on different trials within the same experiment. To date none of the visual studies has provided a similar demonstration.

The findings of Chapter 5 also suggest that there may be similarities between visual and auditory attention in the way that strategies for attentional allocation can affect stimulus processing. The results showed that, if the target of auditory search is a reliable feature singleton, subjects tend to direct their attention towards any singleton in the search array, as this is likely to be an efficient strategy for target detection or discrimination. This strategy leads to auditory attentional capture, as it does in vision (e.g. Pashler, 1988; Theeuwes, 1991a, 1992). However, if the target is not a reliable feature singleton and subjects are forced into a focused feature search mode (in which priority for attentional allocation is given to items containing the specific target feature) then attentional capture does not occur, either in hearing (as demonstrated in Chapter 5) or in vision (e.g. Bacon & Egeth, 1994).

While Chapters 2-5 established some commonalities between the results of spatial visual search tasks and sequential auditory search tasks, Chapter 6 in turn asked whether similarities could be found between the results of these auditory search tasks and a sequential visual search task. Two experiments confirmed that irrelevant singletons could produce interference in a visual sequential task, just as they can in similar auditory tasks.

The finding that very similar AC effects can be found in sequential search tasks in either modality, along with observations of similarities between previous visual AC studies and the current auditory research, provides further support for the idea that there might be similarities between attentional processing in vision and hearing. This research adds to a growing body of auditory research investigating such potential similarities. For example, Dyson & Quinlan (2003) demonstrated that subjects were faster to respond to auditory targets defined by a single feature than to auditory targets defined by a conjunction of features (see also Dyson & Quinlan, 2002; Woods et al., 2001; Woods, Alain & Ogawa, 1998). This is a well-established finding in the study of visual attention (e.g. Treisman & Gelade, 1980), and the fact that it has also been demonstrated in hearing suggests that auditory attention might integrate features in a similar way to visual attention (i.e. individual features are processed in parallel at a preattentive stage, before being integrated at a later stage for which attention is required). Along similar lines, other researchers have found auditory analogues for several well-known visual attentional phenomena including change blindness (e.g. Vitevitch, 2003), AC by uninformative spatial cues (e.g. Spence & Driver, 1997) and the attentional blink (Duncan, Martens & Ward, 1997). Similarly, the findings presented within this thesis establish an auditory version of the phenomenon of AC during search tasks, an effect that had previously only been studied in vision. In this way, the present research contributes to the auditory research described above, demonstrating effects that are analogous to established visual phenomena. Note that we might expect higher-level processes such as feature integration, change blindness, attentional blink and AC to progress along similar lines in both vision and hearing, as these processes operate at a level that is likely to be largely independent from early sensory processing (e.g. Shamma, 2001).

7.3 Implications for crossmodal research

The fact that there appear to be similarities between attentional processes in vision and hearing might suggest that it would also be possible to demonstrate AC crossmodally between the two senses. (Indeed, the very idea that the auditory system acts as an early-warning system would suggest that it is likely that auditory singletons ought to be able to capture attention away from a visual task.)

Spence and Driver (1997) carried out a study with results that are encouraging for the possibility of finding crossmodal AC. 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. Interestingly, when visual rather than auditory cues were used, they only affected performance for visual targets and not for auditory targets. Thus, while auditory cues captured both auditory and visual attention, visual cues appeared only to capture visual attention. Subsequent research has suggested that this asymmetry in Spence and Driver's (1997) crossmodal cuing results might have been due to visual cues directing attention towards more narrowly focused areas of space than auditory cues. Because Spence and Driver's (1997) task involved judgements of the elevation of a target stimulus, the cue stimulus was presented at an intermediate elevation and so did not appear at the exact location of the subsequent target. It is possible that the difference in elevation between visual cues and auditory targets would have prevented cuing effects, because the auditory target would not fall into the relatively narrow attended area. By contrast, the difference in elevation between auditory cues and visual targets would not have prevented cuing effects, as the attended area due to the auditory cue would be broader than that due to the visual cue, and the subsequent visual target would fall within it. In line with this argument, visual cues have been shown to affect performance on auditory tasks using a set-up where visual cues are presented at exactly the same location as subsequent auditory targets (e.g. Ward, McDonald and Lin, 2000).

In the light of these results, it might 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. The present thesis has established auditory and visual versions of a rapid serial search task in which AC by irrelevant singletons can be observed. This provides a basis from which a crossmodal version of the effect could be investigated. Rapid serial sequences of sounds and visual stimuli could be presented simultaneously giving a set-up in which one could examine the effects both of visual singletons in an auditory task and of auditory singletons in a visual task.

Note that there is already research to suggest that auditory deviants can interfere with behavioural performance in a visual task. For example, Escera, Alho, Winkler & Näätänen (1998) showed that responses in a visual discrimination task (in which subjects responded according to whether numbers were odd or even) were less accurate when the number stimulus followed a sound of deviant frequency than when it followed a sound of standard frequency. Similar effects have also been found for intensity and duration deviants (e.g. Escera, Corral & Yago, 2002). However, as was the case in much of the auditory research, the auditory stimuli in these studies often predicted the target, and slow rates of presentation were used so that the overall demands on attentional resources were low. Both of these factors mean that there was little incentive for subjects to attempt to ignore the auditory distractors in these studies and as such the results may be attributable to deliberate allocation of attention to the auditory stimuli, rather than capture of attention by those stimuli. It would be interesting to ask whether irrelevant auditory singletons can capture attention during a visual task even when they do not predict the target and when they are presented in conjunction with a more demanding visual task. In addition, the previous crossmodal studies have tended to focus on the effects of auditory distractors on visual tasks. A fully-factorial design, that also looked at possible visual disruption of auditory tasks, might be a interesting extension of the present experiments.

7.4 Underlying neural mechanisms

This thesis has established the behavioural phenomenon of auditory AC. It would also be interesting to ask about the neural mechanisms underpinning this AC. The literature on the MMN and its associated attentional orienting components suggests that the MMN may be involved, at least to some extent. Recall that the MMN is elicited by sounds that form a change in a repetitive auditory sequence (e.g. Näätänen, 1975; Näätänen, Gaillard & Mäntysalo, 1978, 1980; Näätänen, 1979; Näätänen & Gaillard, 1983; reviewed by Näätänen, 1992). As such, the MMN seems to reflect processes involved in detection of deviants and is therefore unlikely to be related to higher-level processes such as attentional allocation. However, the MMN is also often accompanied by an attentional orienting component, the P3a, suggesting that, under circumstances where there is no competition for attention, deviant sounds tend to attract attention (e.g. Knight, 1984; Näätänen, Simpson & Loveless, 1982; Sams, Paavilainen, Alho & Näätänen, 1985). Thus the P3a may be more likely to reflect neural mechanisms related to auditory AC.

For this reason, an interesting extension of the findings would be to record ERPs during performance of the tasks reported here. However, as there are many differences between the present task and the typical tasks used in the MMN research it is not clear whether the target and singleton stimuli used here would elicit the MMN at all. For example, in the experiments reported here, two "deviant" sounds (the target and the singleton) are often presented in each sequence of four or five sounds, typically occurring one after another. By contrast, the deviants used in the MMN studies appear much less frequently. Thus it is unlikely that the unique sounds used here would be treated as deviants to the same extent as the odd sounds used in the MMN studies. In addition, unlike the present experiments, very few of the MMN studies encouraged participants to ignore the deviant sounds. And recall that the few studies that did encourage participants to focus attention away from the deviant sounds (using strong manipulations of attention, such as dichotic listening tasks) found that this reduced or eliminated the MMN (e.g. Trejo et al., 1995; Woldorff et al., 1991; Woldorff et al., 1998). For both these reasons, it is not clear whether targets and singletons in the present experiments would have elicited the MMN at all. And indeed if they did, this would merely indicate perception of the deviant sound. A more interesting question would be whether any MMN was accompanied by the attentional orienting component (P3a) and perhaps followed by a re-orienting negativity, as this might indicate involuntary capture of attention by the singleton stimulus.

ERP measurements would have been particularly interesting during Experiment 9 (Chapter 4), as this experiment found facilitation due to the presence of an irrelevant singleton feature within the target sound itself. It would be interesting to compare the ERP responses to nontarget singletons (leading to interference) with responses to target singletons (leading to facilitation).

The underlying neural mechanisms of auditory AC could also be investigated through neuroimaging. A recent event-related fMRI study of visual AC (DeFockert, Rees, Frith and Lavie, in press) found that capture of visual attention is associated with activity in frontoparietal areas known to be associated with selective attention. It would be interesting to run a similar fMRI study to identify the neural correlates of auditory AC. In addition, a comparison between the findings of a fMRI study of auditory AC and the findings of the DeFockert et al.'s fMRI study of visual AC could reveal whether there are any shared neural mechanisms underlying AC in both vision and hearing, or whether the activations associated with AC are modality-specific.

7.5 Conclusions

The present thesis has established the phenomenon of auditory AC by irrelevant singletons in serial search tasks. This auditory AC leads to interference if the singleton is presented within a distractor item but reverses to facilitation if the singleton occurs within a target item. I have also shown that auditory AC is influenced by relatively high-level factors such as the subject's strategy for allocation of attention. Finally, the current work has established the phenomenon of non-spatial visual AC in RSVP search tasks. Overall, these results add to a growing body of research demonstrating similarities between attentional processes in vision and hearing.

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