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Perceptual load does not modulate auditory distractor processing

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In vision, it is well established that the perceptual load of a relevant task determines the extent to which irrelevant distractors are processed. Much less research has addressed the effects of perceptual load within hearing. Here, we provide an extensive test using two different perceptual load manipulations, measuring distractor processing through response competition and awareness report. Across four experiments, we consistently failed to find support for the role of perceptual load in auditory selective attention. We therefore propose that the auditory system – although able to selectively focus processing on a relevant stream of sounds – is likely to have surplus capacity to process auditory information from other streams, regardless of the perceptual load in the attended stream. This accords well with the notion of the auditory modality acting as an 'early-warning' system as detection of changes in the auditory scene is crucial even when the perceptual demands of the relevant task are high.

Keywords: Auditory selective attention, Perceptual load, Distractor processing

1. Introduction

Selective attention is a crucial mechanism in making sense of the world around us, as it allows us to focus on important events at the expense of less relevant ones. The determinants of such selective processes have been widely researched. However, over the past fifteen years, one of the most influential theories within visual selective attention has been the perceptual load account (Lavie, 1995; Lavie & Tsal, 1994). The theory holds that perception has a limited capacity, which automatically proceeds until exhausted. As a consequence, the perceptual demands of the relevant task determine whether or not irrelevant stimuli outside the focus of attention are processed. If the relevant task is perceptually easy (low perceptual load), any remaining attentional capacity will automatically be allocated to the surrounding, task-irrelevant stimuli, which in turn may have a detrimental effect on performance of the primary task. However, with a more perceptually demanding relevant task (high perceptual load), all the available capacity will be allocated to the task at hand and little or no irrelevant information will therefore be processed. Although some aspects of these claims have recently been challenged (for example, by the dilution account; e.g. Tsal & Benoni, 2010), overall the theory has received a great deal of support in the visual domain, from both behavioural and neuroimaging studies using a range of different task paradigms (see Lavie, 2005; 2010 for reviews).

Despite the wide-ranging contributions of perceptual load theory to the study of visual selective attention, it has rarely been tested in other sensory modalities. However, if we are to understand attention as it operates in real world environments, it is vital to examine its function in modalities other than vision. In particular, hearing is often claimed to act as an ‘early warning system’ (e.g. Dalton & Lavie, 2004), because it is not constrained by the same physical selection mechanisms as the other senses. For example, hearing can register unexpected changes in the environment from a range of directions (and even in the dark), in contrast to the other senses which have a narrower spatial focus. It is therefore particularly important to investigate whether or not load theory also holds within audition. Indeed, in a comprehensive literature review which laid the empirical foundation for the theory, Lavie and Tsal (1994) argued that the principles would most likely apply in the auditory domain. If the theory does hold, such that distractor processing is influenced by the perceptual load of the task at hand, this would constrain the conception of hearing as an ‘early warning system’ in identifying a wide range of conditions under which such a warning system would be ineffective. If, on the other hand, distractor processing proceeds regardless of levels of perceptual load, this could be taken to strengthen the ‘early warning’ interpretation. Here, we report a detailed examination of this issue from two perspectives. We begin by bringing together the current literature on load theory in audition, before describing our own empirical investigation into the applicability of load theory to the auditory domain.

The dichotic listening studies, which initiated much of the research in this area, demonstrated that very little was remembered of a message presented to one ear when attention was focused on the other ear (e.g. Broadbent, 1958; Cherry, 1953). The attended tasks in these experiments were typically highly perceptually demanding, as participants not only had to attend to the relevant stream but also encode each element in order to repeat back what was said, whilst ignoring the continuous irrelevant stream in the other ear. The fact that very little information from the irrelevant stream could be reported under these conditions might therefore be argued to relate to the high perceptual demands of the relevant task, in line with load theory. However, perceptual load was not the focus of these early studies, so they did not typically include manipulations of the demands of the relevant task. This prevents direct conclusions about the role of perceptual load in the early dichotic listening studies.

Many of the more recent EEG studies of dichotic listening have also addressed the influence of attention on perceptual processing, in particular through investigations of the mismatch negativity (MMN), which is typically elicited by an ‘oddball’ sound deviating from a uniform auditory sequence. The central question has been whether registration of these deviants (as indexed by the MMN) is modulated by the availability of attention. This has been an issue of considerable debate within the field, with many studies suggesting that the MMN can be elicited in the absence of attention (e.g. see review by Näätänen et al., 2007) but others demonstrating a reduced MMN when attention is focused elsewhere (e.g. Alain & Woods, 1997; Müller-Gass, Stelmack & Campbell, 2005; Näätänen, Paavilainen, Tiitinen, Jiang, & Alho, 1993; Treijo, Ryan-Jones, & Kramer, 1995). Overall, it seems that the MMN is only modulated by attentional allocation under certain conditions, such as when the target is highly similar to a deviant in the unattended stream (e.g. see Sussman, 2007, for review). However, it is hard to draw any conclusions from this research in terms of whether auditory perceptual load determines processing of irrelevant information, because, as with the early behavioural studies of dichotic listening (e.g. Cherry, 1953), very few of these studies have manipulated auditory perceptual demands directly.

Nevertheless, some EEG studies of auditory selective attention have included direct manipulations of task demand. One way that this has been achieved has been through varying the presentation rates of the attended stimuli. For example, Parasuraman (1980) measured the amplitude of the N1 (an early negative component susceptible to attentional modulations) that was elicited by both attended and unattended stimuli (separated by ear). With a fast presentation rate, the N1 elicited by stimuli in the attended stream was relatively large compared to the N1 elicited by stimuli in the unattended stream, suggesting that the unattended stream received relatively little processing. By contrast, a slow presentation rate resulted in a smaller difference in amplitude between the N1 responses to attended and unattended stimuli, suggesting that both streams were perceived in this instance. Similarly, Woldorff et al. (1991) found that the MMN response to the deviant stimuli in an unattended ear was attenuated when the rate of presentation of the stimuli for the attended task was increased. In addition, using intracranial recordings, Neelon, Williams and Garell (2011) found an enhancement in grand-average ERP waveforms for both an attended and an unattended channel at slow presentation rates, whereas with faster interstimulus intervals (ISIs) only the ERPs in response to the attended ear were enhanced, implying that the irrelevant stream in the other ear was not processed in this instance. Taken together, these findings suggest that faster presentation of attended stimuli leads to reductions in processing of unattended stimuli, as measured by a range of different ERP components. This suggests that the locus of auditory attention is contingent upon the specific processing demands of the relevant task, providing initial support for the applicability of perceptual load theory to audition.

However, not all studies have found this pattern of results. For example, Gomes et al. (2008) manipulated ISI in a paradigm where participants attended to one out of two auditory channels based on the frequency of the sounds, whilst ignoring the other. The task involved making a button response whenever a tone of lower intensity than standard appeared in the attended channel. The Nd magnitude (the negative difference between ERP waveforms when stimuli are attended and when they are unattended) was utilised to measure the difference between performance in a fast ISI condition and a slower ISI condition. Although perceptual load theory would predict a larger Nd amplitude in the fast ISI condition (as a result of less distraction from the irrelevant channel) in fact the Nd did not change as a function of ISI. Thus there is not yet a consensus regarding the impact of ISI manipulations on auditory distraction. In addition, earlier work on auditory scene analysis (e.g. Bregman, 1990) has indicated that presenting auditory stimuli with smaller temporal separation can strengthen the processes of perceptual segregation in the auditory scene (as argued, for example, by Francis, 2010). This means that manipulations of ISI are potentially confounded by concurrent changes in the strength of perceptual segregation, making it hard to draw conclusions based on this type of manipulation.

Nevertheless, a small number of studies have used manipulations of perceptual load that are not subject to this confound. For example, Alain and Izenberg (2003) presented participants with two streams of sounds, one to each ear, each of which included tuned and mistuned stimuli. Under low load, participants detected infrequent targets defined by short duration in the attended ear. Under high load they were additionally required to report the tuning (tuned vs. mistuned) of these short duration targets. MMN amplitude to short duration deviant stimuli in the unattended ear was decreased in the high load conjunction task (vs. the low load feature task) as predicted by perceptual load theory. However, although the task-irrelevant stream in this study used the same stimuli as the task-relevant stream, the high load task required attention to two different dimensions (such that participants would have needed to implement an ‘attentional set’ for both duration and tuning) whereas the load low task only emphasised duration. This is likely to have resulted in the attentional set being more clearly focused on duration in the load (vs. high) load task. Thus the reduction in MMN amplitude under high (vs. low) load could be related to the reduced priority of duration in the high (vs. low) load task, rather than to differences in the availability of processing capacity. Indeed there is substantial evidence that the attentional set required for the task is important in determining the extent to which task-irrelevant deviants capture attention, both in vision (Bacon & Egeth, 1994; Folk, Remington & Johnston, 1992) and in hearing (Dalton & Lavie, 2007). Therefore, these results cannot be taken as clear support for the applicability of load theory to hearing. Indeed, a more recent task, which is unlikely to have involved changes in the focusing of participants’ attentional set between conditions, failed to demonstrate any differences in MMN amplitude as a function of task demands (Müller-Gass & Schröger, 2007). Participants made judgements to the duration of tones presented binaurally, and task demands were manipulated through the difference in duration between the short and the long tones. Despite the fact that the attentional set between high and low load would have been the same, as both conditions required duration judgements, the amplitude of the MMN elicited by occasional low frequency deviants did not vary across load conditions.

Criticisms relating to changes in the attentional set that participants are likely to adopt only apply to experiments in which the attended and unattended streams are highly similar. By contrast, a recent MEG study (Chait, Ruff, Griffiths, & McAlpine, 2012) required participants to attend to sequences of auditory ‘objects’ (a mixture of pure tones, frequency-modulated tones, glides and white noise) presented to one ear, while ignoring a stream of 30-ms tone ‘pips’ presented to the other ear. Although they found no effect of auditory task load on detection of changes in the unattended stream when these changes constituted a regular pattern becoming irregular, increased load did reduce detection of changes that constituted irregular sequences becoming regular. However, as perceptual load theory was not the focus of this study, the load manipulation in fact involved increased memory demands under high (vs. low) load. This complicates the interpretation of these findings in relation to the question of whether perceptual load theory applies within hearing.

Nevertheless, two recent behavioural studies using manipulations that are likely to have targeted perceptual (rather than memory) demands have suggested that perceptual load theory might hold in the auditory domain. Santangelo, Belardinelli and Spence (2007) found that peripheral auditory cuing effects were reduced when participants were asked to respond to (or simply focus on) a central stream of sounds (both of which might be considered to constitute high perceptual load conditions), compared with when the cueing task was performed on its own (the equivalent of a ‘low load’ condition). Santangelo et al. (2007) concluded that the perceptually demanding central stream exhausted processing capacity so that the auditory cues were not perceived to the same extent, providing support for perceptual load theory. However, because both ‘high load’ conditions involved the presence of an additional auditory stream which was absent in the ‘low load’ condition, it is possible that the reduction in peripheral cueing under ‘high load’ was driven not by the exhaustion of processing capacity but instead by the many other perceptual factors (e.g. focus of spatial attention, perceptual grouping) that are likely to change in the presence (vs. absence) of additional auditory stimuli.

Nevertheless, Francis (2010) found results suggestive of an auditory perceptual load effect in a set-up in which the task stimuli were closely matched between high and low load conditions. He presented participants with two concurrently spoken words, both of which could be either ‘bead’ or ‘bad’, and asked them to attend to a speaker of one gender while ignoring a speaker of the other gender. The words were accompanied by an additional tone, which could be of high or low pitch and amplitude-modulated or not. The task was to indicate on each trial which of the two words had been spoken in the relevant voice but only when the tone followed a specific prerequisite. This was determined by a single feature of the tone in the low perceptual load condition, and by a conjunction of the features in the high load condition. Distractor processing was measured in terms of the interference effects of incongruent (vs. congruent) distractors. There was some suggestion of reduced interference in the RTs under high (vs. low) perceptual load, however the relevant statistical interaction between load and distractor congruency did not approach significance in either of the two reported experiments ($F < 1$ in both cases). It is therefore difficult to make strong claims about the effects of auditory perceptual load based on these findings.

Overall, given the mixed pattern of findings reviewed above, firm conclusions regarding the role of perceptual load in auditory selective attention cannot presently be made. We set out to provide a fuller and more robust investigation of this issue, based on four new experiments using two different load manipulations (all of which were based on well-established manipulations of visual perceptual load) and two different measures of distractor processing.

2. Experiment 1A

In our first two experiments we presented participants with rapid sequences of sounds and manipulated perceptual load by varying the perceptual similarity between the target and the nontarget sounds, as is commonly done within the visual perceptual load literature (e.g. Beck & Lavie, 2005; Forster & Lavie, 2008). Thus, under high load nontarget letters were similar-sounding to the target letters which made it more taxing to identify the target. Conversely, under low load the target letters were easily identifiable amongst the nontarget letters. A distractor letter sound — either congruent or incongruent with the target — was presented on two thirds of the trials (see Figure 1 for a schematic representation of the task). According to load theory, the distractor should produce more interference (as indicated by stronger congruency effects) under low (vs. high) perceptual load.

2.1. Method

2.1.1. Participants.

16 participants (2 male, one left-handed) were recruited at Royal Holloway, University of London, in exchange for course credits. The average age was 23, ranging from 18 to 40 years. Participants in all experiments reported normal or corrected-to-normal vision and normal hearing. Informed consent was obtained from all participants and all testing protocols were approved by the Departmental Ethics Committee.

2.1.2. Apparatus and stimuli.

The experiment was run on a PC using the PST E-prime 2.0.8.90 software. Sounds were presented at an average level of 60 dB on Sony SRS – A201 speakers which were placed in line with the ear position on each side of the head, 40 cm apart from each ear. Recordings of spoken letters were selected from stimuli used by Shomstein and Yantis (2006). (We used letter stimuli rather than words as to avoid any semantic influences on task performance). The duration of each stimulus was 240 ms, followed by 10 ms of silence such that each WAV file lasted 250 ms in total. Each trial consisted of a rapid sequence of six letters spoken in a female voice. Mono source recordings of these stimuli were written to both channels, so that their perceived location was at the centre of the stereo field (see Francis, 2010, for a similar method of determining stimulus location).

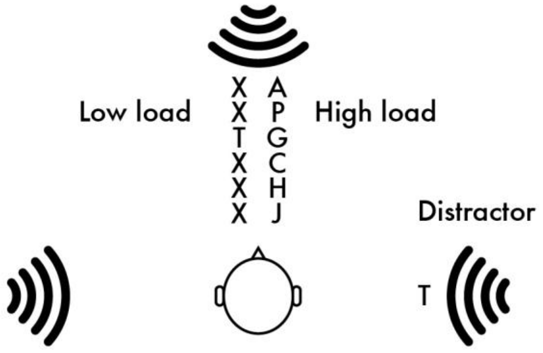

Figure 1. Example of a low and a high load trial, in which the target (P or T) could appear in position 2-5 of the centrally presented sequence. The distractor sound (P or T) was presented from either the left or the right speaker.

Although most studies of visual perceptual load present stimuli simultaneously, we used sequential presentation because this is often considered more appropriate for auditory stimuli. Indeed, it has been argued that temporal separation of auditory stimuli might be comparable with spatial separation of visual stimuli (e.g., Kubovy, 1981) based on the idea that the auditory system processes spatial location with lower priority than other stimulus attributes, such as timing and frequency (e.g., visual areas of the cortex are spatiotopically organised, whereas auditory cortex is organised primarily according to frequency; Merzenich, Colwell & Andersen, 1982). In addition, one recent study did in fact demonstrate perceptual load effects using a sequential visual presentation (Carmel, Thorne, Rees, & Lavie, 2011), thus this precedent also already exists in the visual domain.

Participants made button-press discrimination responses according to the identity of a target letter (P or T, with equal likelihood) which was present on each trial. The target was never presented in the first or last serial position and was equally likely to appear at any of the four remaining serial positions. Participants were asked to respond as soon as the target letter was perceived, rather than listening to the full sequence prior to responding.

In the high perceptual load condition, the five nontarget letters making up the rest of the sequence were drawn at random (without replacement) from a list of six letters (A, C, H, G, J, and K). In the low perceptual load condition, the five nontarget letters were all X's. Letters were separated by silent ISIs of 60 ms, resulting in a total duration of 1740 ms for each sequence.

A distractor letter (P or T, spoken in a male voice) appeared on two thirds of the trials, at the mid-point of the sequence (i.e. in between the third and the fourth letter sound) and from the left or right speaker with equal likelihood. Thus, the distractor overlapped with the final 90 ms of the third letter and with the initial 90 ms of the fourth letter. The distractor was either congruent with the target (one third of trials) or incongruent (one third of trials) and remained absent on the remaining third of the trials.

2.1.3. Procedure.

The experiment took place in a quiet testing room. Participants were asked to attend to the female voice whilst ignoring the male voice, and also to maintain a central focus of attention as the letter stream would always appear centrally. Equal emphasis was placed on speed of responses and on accuracy. Half of the participants pressed the 0 key on the numerical keyboard whenever they heard the target letter 'P' and the 2 key whenever they heard the target letter 'T'. For the other half of the participants, this response pattern was reversed. In both cases, participants used the index and middle fingers of their right hand to press 0 and 2 respectively. A chin rest was used to control for possible head movements. 500 ms prior to each trial, a grey fixation cross was presented centrally on the screen on a black background. The cross remained visible throughout the trial. Immediately after response, visual feedback appeared on the screen for 500 ms. The feedback consisted of "Correct" presented in blue letters for correct responses, "Oops" in red letters for incorrect responses, and “No response detected” in blue letters if participants had failed to respond within 3000 ms from the onset of the letter sounds. A new trial commenced after the feedback, with the re-appearance of the fixation cross.

Participants completed two practice blocks in the presence of the experimenter — one high load and one low load block with 12 trials in each. This was followed by ten experimental blocks of 48 trials in each, with self-timed breaks in between blocks. High and low perceptual load was blocked, and the order of the blocks was counterbalanced across participants, so that half of them performed the blocks in the order high, low, low, high, while the inverse order was performed by the other half.

2.2. Results and discussion

Data from one participant were excluded due to technical problems in data recording. Data from an additional participant were also excluded as mean RTs (M = 855 ms) were more than 2 SDs higher than the group mean RTs (M = 550 ms, SD = 112). For the remaining 14 participants, incorrect responses and responses above 2000 ms (1% of the total number of trials) were excluded from the RT analysis. When applicable, we used a Bonferroni corrected alpha of $p < .017$ to account for multiple testing. Table 1 gives mean correct RTs and error rates for Experiments 1A and 1B as a function of perceptual load and distractor congruency.

A 2 (perceptual load: low, high) x 3 (distractor congruency: congruent, absent, incongruent) repeated measures ANOVA on the RT data revealed a significant main effect of perceptual load, $F(1,13) = 11.36$, $MSE = 3936.57$, $p <.01$, $\eta_p^2 = .466$. Responses were slower in the high load condition (M = 551 ms) in comparison with the low load condition (M = 505 ms), indicating that the load manipulation was successful. There was also a significant main effect of distractor congruency, $F(1.2, 15.71) = 14.51$, $MSE = 1012.13$, $p <.001$, $\eta_p^2 = .527$, Greenhouse-Geisser corrected. Participants were slower in their responses in the incongruent condition (M = 546 ms) compared to the distractor absent condition (M = 526 ms, $t(13)$, 4.33, $p < .001$) and also in comparison to the congruent condition (M = 511 ms, t(13), 3.99, $p < .01$). There was a near-significant difference (following Bonferroni correction) in RTs between the congruent and the absent conditions, t(13), 2.7, p = .018, with slower responses in the absent condition. However, there was no significant perceptual load x distractor congruency interaction revealed, F(2,26) = 1.37, MSE = 411.68, p = .272, $\eta_p^2 = .095$ (see Table 1).

The overall interference effect (calculated by subtracting congruent RTs from incongruent RTs) was equally large under high load (M effect = 36 ms) as under low load (M effect = 35 ms, see Table 1) and an additional t-test confirmed that this observed interference effect under high load was indeed significant, t(13) = 3.29, p < 01. This lack of any slight trend towards a reduced interference effect under high load conditions makes it highly unlikely that our failure to find a significant interaction between load and distractor congruency relates to a lack of power.

This finding remained consistent in a further analysis designed to rule out any effects of the overall increase in RT seen under high (vs. low) load. We expressed the distractor interference effects (incongruent RTs – congruent RTs) as a proportion of baseline mean RT and still found no difference in these scores between high (6%) and low load conditions (6.7%, t(13) < 1).

Error rates in this experiment were low and showed little variation between conditions. The mean error rates for each experimental condition were entered into a 2 (perceptual load: high, low) x 3 (distractor congruency: absent, congruent, incongruent) repeated measures ANOVA, which revealed no significant main effects of load, F (1,13) <1, or congruency, F(1,13) = 2.31, MSE = .001, p = .12, $\eta_p^2 = .151$, and no significant interaction, F(1,13) <1.

Overall, despite clear evidence of a robust manipulation of perceptual load, Experiment 1A found no suggestion of the reduced distractor processing under high (vs. low) load that is predicted by perceptual load theory. However, because it is hard to be precise about the level of perceptual load imposed by a particular task, findings of this type are always open to the alternative interpretation that the load manipulation simply wasn't strong enough to exhaust capacity and thus elicit the predicted pattern of results. For this reason, we aimed to increase the strength of the load manipulation in Experiment 1B.

Table 1. Mean correct reaction times (milliseconds) and error rates (%) for Experiment 1A and 1B as a function of perceptual load and distractor congruency. SDs are in brackets.

	Perceptual load					
	Low			High		
Experiment	Congruent	Absent	Incongruent	Congruent	Absent	Incongruent
1A						
Mean	486 (75)	507 (85)	521 (88)	536 (68)	544 (68)	572 (95)
% Errors	7 (.05)	7 (.05)	7 (.03)	6 (.05)	6 (.07)	8 (.06)
1B						
Mean	509 (79)	N/A	542 (75)	608 (84)	N/A	642 (87)
% Errors	4 (.03)	N/A	5 (.04)	5 (.03)	N/A	9 (.06)

3. Experiment 1B

In Experiment 1A, distractor interference was seen across both levels of perceptual load. Although there was evidence for increased perceptual demands under high load compared to low load, it may be argued that the task was not demanding enough to exhaust all processing capacity. Experiment 1B thus sought to increase the perceptual load of the flanker task through a more rapid presentation of the letter sequence.

3.1. Method

3.1.1. Participants.

14 new participants (three male) were recruited. The average age was 21 (ranging from 19 to 22) and two were left-handed (one male, one female).

3.1.2. Stimuli and procedure.

The stimuli and procedure were similar to those of Experiment 1A, with a few exceptions. The durations of the files containing the letters (previously 250 ms) were shortened to 180 ms in order to speed up the rate of presentation, resulting in a total duration of 1330 ms for each sequence. We also presented the distractor on all trials to reduce the possibility that it might capture attention due to its comparative novelty. Along similar lines, we also reduced the distractor's intensity by 20% relative to the other sounds, in order to reduce its relative salience. Participants completed 14 experimental blocks with 32 trials in each, preceded by two practice blocks.

3.2. Results and discussion

RTs longer than 2000 ms were excluded (1% of the overall trials) and for the RT analysis, incorrect trials were also omitted. A 2 (perceptual load: low, high) x 2 (congruency: congruent, incongruent) repeated measures ANOVA revealed a main effect of load, $F(1,13) = 63.99$, $MSE = 2168.47$, $p < .0001$, $\eta_p^2 = .831$. Participants were slower in their responses under high load ($M = 625$ ms) than under low load ($M = 526$ ms), indicating that the perceptual load manipulation was successful. The main effect of distractor congruency was also significant, $F(1,13) = 39.1$, $MSE = 414.31$, $p < .001$, $\eta_p^2 = .750$, with faster RTs in the congruent condition ($M = 559$ ms) than in the incongruent condition ($M = 593$ ms). However, the load x distractor congruency interaction did not approach significance, $F(1,13) < 1$.

Similarly to experiment 1A, the overall interference effect was equally large under high load (M effect = 34 ms) as under low load (M effect = 33 ms, see Table 1) and an additional t-test confirmed that the effect was significant under high load, $t(13) = 3.31$, $p < 01$. Once again, this lack of any suggestion of a difference in the interference effects makes it highly unlikely that the failure to find any interaction between load and distractor congruency relates to a lack of power.

Also as in the previous experiment, we calculated distractor interference as a proportion of mean RT under each load condition (high, 5.6%; low, 6.5%) and found no significant difference, $t(13) < 1$. This further supports the findings from the main analysis, indicating that distractor interference did not differ as a function of perceptual load even when accounting for the overall increase in RT under high load.

The analysis of the error data mirrored these results very closely. Mean error rates were entered into a 2 (perceptual load: low, high) x 2 (congruency: congruent, incongruent) repeated measures ANOVA, which revealed a main effect of load, $F(1,13) = 6.75$, MSE = .002, $p <.05$, $\eta_p^2 = .342$. More errors were evident for high (M=6%) compared to low perceptual load (M = 5%), providing additional evidence that the load manipulation was successful. There was also a significant main effect of congruency, $F(1,13) = 16.22$, MSE = .002, $p <.001$, $\eta_p^2 = .555$, with higher errors in the incongruent condition (M = 7%) compared with the congruent condition (M = 4%). Once again, the load x congruency interaction did not reach significance, $F(1,13) = 2.88$, MSE = .001, $p = .113$, $\eta_p^2 = .181$ (and note that any trend towards such an interaction in fact reflects the opposite pattern from that predicted by load theory, with stronger distractor interference under high load (mean effect = 4%) than under low load (mean effect = 1%), see Table 1).

Overall the load manipulation in Experiment 1B (mean effect = 99 ms) was clearly strengthened by comparison with that of 1A (mean effect = 50 ms). Nevertheless, the predicted perceptual load effects on distractor processing still did not arise. Thus the two experiments in this series so far have both demonstrated clear auditory distraction effects that remained unaffected by the level of perceptual load in an ongoing relevant task.

It is important for any test of perceptual load theory that the relevant sounds through which load is manipulated are clearly separable from the task-irrelevant distractors. In Experiments 1A and 1B we used three important cues to ensure effective segregation between the relevant and irrelevant streams. The first was speaker gender (male vs. female voice). The second was spatial location (with the relevant stimuli presented centrally and the distractors presented at clearly separate peripheral locations). The third was temporal offsetting, such that each distractor overlapped with two successive items from the relevant stream and thus could not be accommodated within the ongoing train of onsets in the relevant stream. Taken together, these cues should have delivered very clear segregation between the distractor and the task-relevant items. We also note that Experiments 2A and 2B used a dichotic listening design which will have ensured even stronger separation.

In summary, the failure across Experiments 1A and 1B to demonstrate the predicted perceptual load effects suggests that load theory might not apply to the auditory modality, raising interesting questions about the ways in which perceptual demands might be handled differently in vision and hearing. However, before making firm conclusions we sought to test our findings in a completely different context where the impacts of perceptual load are measured in terms of awareness rather than distractor interference. We used the inattentional deafness paradigm (e.g. Mack & Rock, 1998; Dalton & Fraenkel, 2012) to measure participants' noticing of unexpected, task-irrelevant auditory stimuli under high and low levels of perceptual load.

4. Experiment 2A

Previous studies using visual stimuli have found increased susceptibility to inattentional blindness (i.e. reduced noticing of an unexpected task-irrelevant stimulus) under high (vs. low) perceptual load, in line with the predictions of load theory (e.g. Cartwright-Finch & Lavie, 2007). Here, we asked whether similar effects would be observed in hearing, using an inattentional deafness task. Participants responded to targets presented in one ear while ignoring white noise presented to the other ear. In the low perceptual load condition, responses were determined by the single feature of stimulus duration. In the high load condition, responses were determined by the conjunction of duration and frequency. This type of load manipulation is now well-established, both in vision (e.g. Lavie, 1995, Experiments 2A and 2B) and audition (Francis, 2010). On the final trial a critical stimulus (the spoken word "cat") was added to the white noise channel and participants' awareness of this word was then investigated.

4.1. Method

4.1.1. Participants.

45 people (Note 1) aged between 15 and 56 (mean age 27) participated, either voluntarily as part of a research demonstration (in the case of visiting school groups) or in return for £2 (when recruited from the Royal Holloway campus). A further seven participants were tested but excluded from further reporting due to technical problems in data collection.

4.1.2. Apparatus and stimuli.

The experiment was programmed in PST E-Prime 2.0, and ran on a PC laptop with Sony MDR-V150 headphones. Auditory stimuli were prepared in Cockos REAPER digital audio workstation software. All instructions were displayed onscreen, and participants' responses were made via keyboard presses, with the exception of the responses to three questions which followed the critical and control stimuli, and which were recorded manually by the experimenter.

Non-critical stimuli consisted of white noise lasting 1500 ms, presented in either the left or right channel and combined with one of four non-critical tones, presented after 500 ms in the other channel. The non-critical tones were either long (800 ms) or short (500 ms) in duration and either low (180 Hz) or high (520 Hz) in frequency. Two critical stimuli were created by adding the critical word "cat" (spoken in a female voice) to the white noise channel of the two non-critical stimuli containing the long duration, low frequency non-critical tone (in either the left or right channel). The critical word lasted 350 ms and was presented after 600 ms in the same channel as the white noise (such that its onset and offset both occurred during presentation of the non-critical tone). See Figure 2 for a visual description of the final critical trial.

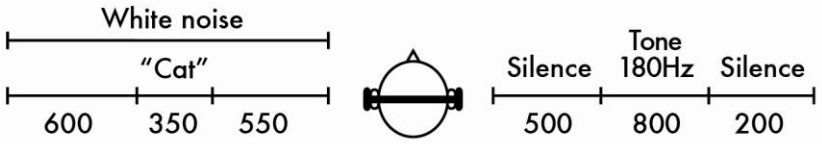

Figure 2. Example of the final critical trial showing the durations in milliseconds of each component of the task stimuli presented to each ear. The target (presented to one ear) always consisted of a long, low frequency tone. The critical sound "cat" was presented over white noise which was delivered to the other ear.

4.1.3. Procedure.

On each trial, participants were asked to make judgements about the tone that was played to their attended ear (left for 50% of the participants, right for the other 50%) while white noise was played to the unattended ear. Half of the participants were allocated to the low load condition, in which they responded according to whether each non-critical tone was long ('Z' key) or short ('M' key) in duration. The remaining participants were allocated to the high load condition, in which they responded according to a conjunction of the tone's duration and its frequency ('Z' key for 'long and low' or 'short and high', 'M' key for 'long and high' or 'short and low'). Responses were measured from the onset of the target tone. In order to minimise the memory demands of the task, written key reminders were displayed onscreen throughout the task. These consisted of the letter Z at the left of the screen with a description of the tones for which that was an appropriate response, e.g. ‘Z: long + low, short + high’) along with the letter M at the right of the screen along with the description of the relevant tones for that response. Participants were told in the pre-task instructions that they did not need to remember the key-response combinations. On-screen feedback was presented immediately following each key press response (“Correct!” in blue or “Incorrect” in red) or after 5 s if no response was detected (“No response detected” in red).

A practice block of 16 trials preceded an experimental block of nine trials. Both blocks included equal numbers of each pitch-duration combination, presented in a random order. On the 9th trial of the experimental block, the critical word (“cat”) was played against the white noise in the unattended ear simultaneously with the target tone in the attended ear. Unlike the preceding 24 randomised trials, the target stimulus in the attended ear during the final (critical) trial was always the same (long and low). After making the usual key-press response to the attended target, participants were then presented with the critical question: “Did you hear anything other than the tone and the white noise on the previous trial?” and required to respond Y or N for “yes” or “no”. This question was presented to all participants exactly 5s after the onset of the critical stimulus, regardless of the timing of their task-related key response.

Participants who answered “yes” to this question were then asked to give the experimenter some more information about what they heard. Those who mentioned the word “cat” in their answer at this stage were categorised as having ‘identified spontaneously’. Those who did not use the word “cat” in their description were asked to choose a word from a list of six words (cat, cake, coat, flat, flake, float) presented in a random order, along with the instruction: “Please choose the word that sounds closest to the additional sound that you heard”. Those who chose “cat” from this list were categorised as having ‘recognised from list’. Participants who responded “no” to the critical question or who failed to choose “cat” from the forced choice list were categorised as having ‘failed to recognise’.

In a final control trial, we examined whether the critical stimulus was clearly audible under conditions of full attention. All participants were played the critical trial for a second time, but this time they were asked to ignore the tone and the white noise and listen out for anything else. Participants who failed to recognise the critical stimulus on this trial were excluded from further analysis, since for these people any failure to hear the critical stimulus on the first playing may have been related to physical audibility rather than attentional allocation.

4.2. Results and discussion

The data from five participants were removed because of a failure to report the critical stimulus on the control trial. The remaining 40 participants were distributed equally between both load conditions (high vs. low) and attended side (left vs. right). There were no effects of attended side on responding, ($\chi2$ (1, N = 40) = 0.14, $p > .70$) so we combined the groups for subsequent analyses.

4.2.1. Attention task performance.

In order to confirm that our perceptual load manipulation had been successful, we compared the performance of the high and low load groups on the non-critical tone classification task. Independent t-tests confirmed that correct RTs were significantly longer in the high load task (M = 1941 ms) than the low load task (M = 1230 ms, t(38) = 6.03, $p < .01$). Note that participants would have been unable to start making decisions about the duration of the tones until at least 500 ms had passed (because this was the duration of the shorter tone) and this makes the RTs appear longer than might otherwise have been expected for a task of this type. Error rates were also significantly higher in the high (M = 14%) than the low load task (M = 1%, t(38) = 2.72, p = .01).

4.2.2. Critical stimulus detection performance.

Table 2 indicates the number of participants who identified, recognised and were ‘deaf’ to the critical stimulus in Experiments 2A and 2B, as a function of perceptual load condition. For the purposes of analysis, the ‘identified’ and ‘recognised’ groups were combined into a single ‘aware’ group, as they had both demonstrated clear processing of the critical stimulus. They were compared with the ‘deaf’ group who had all failed to recognise the stimulus from the forced choice questionnaire. 25% of participants in the high load group were thus identified as ‘deaf’, as compared with 20% in the low load group. This difference did not come close to significance ($\chi 2$ (1, N = 40) = 0.14, p > .70). Thus there was no difference in the likelihood of noticing the critical stimulus between the high and low perceptual load groups, despite a clearly successful perceptual load manipulation. Power analysis indicated that, for a one-tailed test with an alpha level of 0.05, 30 participants (15 in each group) would be required to detect an inattentional deafness effect of the magnitude reported by Macdonald and Lavie (2011) with a power of 0.8. It therefore seems unlikely that our failure to demonstrate the predicted load effects is related to a lack of power. Indeed, these findings are in line with those of both previous experiments, despite our use of a different measure of auditory distractor processing. However, because the current experiment involved a change of paradigm we ran a second version in order to ensure that the findings would generalise beyond this particular experiment.

Table 2. Numbers of participants who identified, recognised and were ‘deaf’ to the critical stimulus in Experiments 2A and 2B, as a function of perceptual load condition

		Response to critical stimulus		
	Perceptual load condition	Identified spontaneously	Recognised from list	Failed to recognise (‘deaf’)
Experiment 2A	High	9	6	5
	Low	8	8	4

Experiment 2B	High	9	2	5
	Low	7	4	5

5. Experiment 2B

Here we sought to provide a final test of the applicability of load theory to hearing using a modified version of the task used in the previous experiment. The main change we made was to replace the non-critical pure tones of Experiment 2A with spoken words, in order to reduce the chances of the critical stimulus capturing attention due to its uniqueness (e.g. Dalton & Lavie, 2004).

5.1. Method

The methods were the same as for Experiment 2A with exceptions as noted in the following sections.

5.1.1. Participants.

36 people aged between 18 and 35 (mean age 22) participated in return for £2. A further seven participants were tested but excluded from further reporting due to technical problems in data collection.

5.1.2. Apparatus and stimuli.

The non-critical pure tones used in Experiment 2A were replaced with non-critical spoken words, all of which were created from a single recording of the word “since” spoken in a female voice. The duration was manipulated to give a long (1 s) and short (700 ms) version, and the pitch was manipulated to give a low version (pitch-shifted down 3 semitones from the original recording) and a high version (shifted up 2 semitones). These values were chosen as the largest pitch-shifts possible in each direction while still retaining a reasonably natural speech sound. The pitch shift and time stretch was implemented using the zplane élastique 2.0 Pro algorithm in REAPER. Whereas in Experiment 2A the white noise had been played only in the unattended ear, in the present experiment it was played to both ears throughout the experiment. The critical stimulus was the word “speech” spoken in the same voice as the non-critical words. It lasted for 1s and was always presented in the unattended ear, at the same time as the long, low version of the target word “since” was presented in the attended ear. The words “since” and “speech” were chosen from a bank of previously-recorded single-syllable, frequent, neutral words. Pilot testing suggested that the word “since” was particularly robust to the required duration and pitch manipulations.

5.1.3. Procedure.

Key reminders were now displayed at the centre of the screen and given for the ‘Z’ key only, in order to reduce the amount of text on screen. A practice block of eight trials preceded an experimental block of 17 trials. The critical stimulus (“speech”) was presented on the 17th experimental trial. The forced-choice recognition questionnaire contained the words ‘speech’, ‘each’, ‘seat’, ‘feet’, ‘which’, and ‘fence’.

5.2. Results and discussion

The data from four participants were removed because of a failure to report the critical stimulus on the control trial. The remaining 32 participants were distributed equally between both load conditions (high vs. low) and attended side (left vs. right). There were no effects of attended side on responding, ($\chi2$ (1, N = 40) = 0) so we combined the groups for subsequent analyses.

5.2.1. Attention task performance.

Independent t-tests confirmed that our perceptual load manipulation had been successful. Correct RTs were significantly longer in the high load task (M = 1624 ms) than the low load task (M = 1212 ms, t(30) = 4.15, p < .01). There was also a trend for higher error rates in the high (M = 14 %) versus the low load task (M = 8 %, t(30) = 1.44, p = .08).

5.2.2. Critical stimulus detection performance.

As in Experiment 2A, we combined the ‘identified’ and ‘recognised’ groups into a single ‘aware’ group, for the purposes of comparing them with the ‘inattentionally deaf’ group. Levels of inattentional deafness were marginally higher than in the previous experiment, with 31 % of all participants classified as ‘deaf’. However, as shown in Table 2, detection performance was identical under high and low load, with 11 participants in each group classed as ‘aware’ and five in each group classed as ‘deaf’ (making statistical comparison redundant). Recall that, as discussed in relation to Experiment 2A, this null effect is unlikely to reflect a lack of power, because a total of 30 participants would provide sufficient power to detect an effect of the magnitude reported by Macdonald and Lavie (2011). Instead, this experiment clearly converges with Experiment 2A and the two previous experiments, strengthening the suggestion that the level of perceptual load in an ongoing auditory task does not impact on people’s likelihood of noticing an unexpected task-irrelevant auditory critical stimulus.

6. General discussion

Overall, across four experiments using two different paradigms (both using a different perceptual load manipulation) our findings remained remarkably consistent. The level of perceptual load did not affect distractor processing in any of the experiments, despite robust and significant load manipulations throughout. In Experiments 1A and 1B the stimuli were presented in sequences and we varied the perceptual similarity between targets and nontargets to achieve the load manipulation. In Experiments 2A and 2B the stimuli were presented simultaneously, and we manipulated load using a feature versus conjunction task. The fact that we found no evidence to support load theory, despite this variety of tasks and load manipulations, leads us to conclude that the theory seems not to apply to the auditory modality.

The possibility will always remain that modulation of distractor processing by auditory perceptual load might be observed if one used even more extreme manipulations of load than we used in these studies. However, the lack of any trend towards an influence of load on distractor processing in any experiment makes this possibility seem unlikely. For example, the load manipulation in Experiment 1B was deliberately strengthened (in fact, doubled) in comparison to that of Experiment 1A without any change in the findings.

We note that these results generalised across two different measures of distractor processing. Experiment 1 used a response competition design, in which the level of distractor processing is inferred from distractor congruency effects on RTs and error rates. By contrast, Experiment 2 assessed distractor processing in terms of participants' reported awareness of an unexpected task-irrelevant stimulus. This allowed us to test for perceptual load effects at two different stages of distractor processing: whereas congruency effects relate to relatively late response-level processing, awareness measures are likely to reflect processing at an earlier stage. This convergence of findings across the two different measures strengthens the claim that auditory distraction might not be determined by the perceptual load of the relevant task. Along similar lines, it is also important that our results agreed across both sequential and simultaneous presentation methods, as these are likely to be subject to different processing constraints (e.g. Alain & Izenberg, 2003).

Previous research in this area has produced a conflicting pattern of results. On the one hand, Gomes et al. (2008) found no difference in ERP measures of auditory distractor processing under high and low perceptual load, which they manipulated using ISI. However, changes in ISI during auditory presentation can also lead to changes in the strength of perceptual grouping (e.g. Bregman, 1990), meaning that ISI-based load manipulations are open to this possible confound. For this reason we avoided this type of manipulation in the current experiments. On the other hand, Alain and Izenberg (2003) did provide some evidence for auditory perceptual load effects through their demonstration of a reduced MMN response to deviant distractors under a high load conjunction task versus a low load feature task. However, their load manipulation may also have caused broader changes in attentional set adopted by the participants, which could have affected processing of the unattended as well as the attended stream (because these were highly similar). Thus it is hard to be sure that the reduction in MMN amplitude under high perceptual load occurred as a result of increased perceptual demands rather than changes in attentional set. Our experiments are not open to alternative explanations along these lines (with the possible exception of Experiment 2B, which also used a feature-vs.-conjunction load manipulation and a distractor that was similar to the targets) and our failure to demonstrate the predicted perceptual load effects strengthens the possibility that factors relating to attentional set played a role in their findings. Finally, Francis (2010) also found some evidence for reduced distractor interference in a spoken word classification task under high perceptual load (requiring the processing of feature conjunctions) by comparison with low load (requiring only the processing of single features). These findings (although not confirmed by the analyses that are conventionally used to demonstrate perceptual load effects) were the most promising with respect to the question of whether perceptual load theory can be applied to the auditory domain and indeed Francis (2010) made just this claim. However, our findings are hard to reconcile with this position. Instead, they converge clearly with previous suggestions (e.g. Gomes et al., 2008) that auditory distraction is not influenced by the perceptual load of a relevant auditory task.

These findings are also in line with a cross-modal study suggesting that auditory distraction can persist regardless of the perceptual load of a relevant visual task (Tellinghuisen & Novak, 2003). However, there is very little research in this area and a consensus on the question of possible cross-modal perceptual load effects has not yet been reached (see, for example, Macdonald & Lavie, 2011, for contrasting findings).

Our findings raise interesting questions about the ways in which perceptual demands might be handled differently in vision and hearing. Load theory, based predominantly on evidence from vision, proposes that perception can only be selective if the task is sufficiently demanding to exhaust capacity. By contrast, Gomes et al. (2008) argued that the allocation of processing resources might proceed with more flexibility in the auditory system. More specifically, they claimed that capacity may not automatically be allocated in full, but may instead be controlled in a more voluntary manner. However, the mechanism behind this proposed flexibility remained unspecified. And indeed, we would argue that there might be a simpler explanation for the findings. Whereas the spatial selectivity of vision provides a mechanism whereby processing capacity can be focused relatively strongly on selected portions of sensory input (for example, the restricted area of the visual field falling on the fovea is significantly over-represented throughout visual processing; Azzopardi & Cowey, 1993) the auditory system does not allow such specific focusing of capacity. Instead, auditory selection proceeds more through perceptual segregation of the scene into 'streams' (Bregman, 1990) upon which attention can then be focused (Shinn-Cunningham, 2008). However, this focusing of attention on a particular stream is unlikely to produce such strong selection as is delivered within vision. Thus even if a particular stream is selected, it is unlikely that the listener will be able to dedicate all available processing capacity to that stream alone. The auditory system therefore seems more likely than the visual system to retain some spare processing capacity at all times. This might provide a mechanism whereby auditory distractors can be processed in addition to an ongoing task, regardless of the demands that the task imposes. Indeed, this would fit with previous suggestions that the auditory system has an 'early warning' function (e.g. Dalton & Lavie, 2004), in which case task-irrelevant sounds should receive some processing, because they may reflect important changes in the environment.

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Footnotes

1. Note that the increase in participants from Experiment 1 is because Experiment 2 used a between-participants design whereas the design of Experiment 1 was within-participants.

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