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Missing a Trick: Auditory Load Modulates Conscious Awareness in Audition

Jake Fairnie
University College London

Brian C. J. Moore
University of Cambridge

Anna Remington
University College London

In the visual domain there is considerable evidence supporting the Load Theory of Attention and Cognitive Control, which holds that conscious perception of background stimuli depends on the level of perceptual load involved in a primary task. However, literature on the applicability of this theory to the auditory domain is limited and, in many cases, inconsistent. Here we present a novel "auditory search task" that allows systematic investigation of the impact of auditory load on auditory conscious perception. An array of simultaneous, spatially separated sounds was presented to participants. On half the trials, a critical stimulus was presented concurrently with the array. Participants were asked to detect which of 2 possible targets was present in the array (primary task), and whether the critical stimulus was present or absent (secondary task). Increasing the auditory load of the primary task (raising the number of sounds in the array) consistently reduced the ability to detect the critical stimulus. This indicates that, at least in certain situations, load theory applies in the auditory domain. The implications of this finding are discussed both with respect to our understanding of typical audition and for populations with altered auditory processing.

Keywords: auditory attention, perceptual load, conscious awareness, selective attention

Selective attention is the ability to focus on a particular aspect of our environment while ignoring others: for example, concentrating on the road when driving and not being distracted by a helicopter overhead, Beyoncé on a billboard, or a new shop window display. This ability to filter stimuli is vital, because our brain has a limited information-processing capacity and we are unable to consider every aspect of the world around us. Over the past few decades, one of the theories that has informed our understanding of how selective attention operates is the "Load Theory of Attention and Cognitive Control" (Lavie, 1995, 2005). The theory states that the extent of processing of a stimulus that is irrelevant to the main task depends on the amount of perceptual load (the amount of potentially relevant information) involved in the main task. When engaging in a task that consumes all available capacity (i.e., a task involving high perceptual load), perception of task-irrelevant stimuli is reduced or eliminated. In contrast, when engaging in a task that does not occupy our full capacity (i.e., a task involving low perceptual load), any spare capacity will automatically "spill over" and result in the perception of irrelevant stimuli.

A great deal of empirical support for load theory has subsequently emerged, but this has predominantly come from studies assessing visual perception (see Lavie, 2005; and Lavie, 2010 for reviews). Though the original framework was, in part, based on observations of auditory processing (Lavie & Tsal, 1994), very few previous studies have systematically assessed load theory within the auditory domain.

Here we outline the few studies that have begun to investigate the impact of auditory load, before offering a novel paradigm for systematically assessing load theory in the auditory domain. We begin, however, by discussing cross-modal applications of load theory: studies that are not solely rooted in audition but have an auditory component.

Cross-Modal Studies of Load Theory

A number of studies have employed cross-modal designs where auditory perception is assessed under various levels of visual load. This literature, however, paints a mixed picture. Raveh and Lavie (2015) found that high visual load in a primary task reduced the extent of auditory processing in a secondary task, consistent with load theory. This pattern of reduced auditory processing under high visual load (increased "inattentional deafness") has been found with various other visual paradigms (e.g., visual tracking task, Isreal, Wickens, Chesney, & Donchin, 1980; line-length discrimination, Macdonald & Lavie, 2011) and with a range of different auditory tasks (e.g., frequency discrimination, Kramer, Sirevaag, & Braune, 1987; tone counting, Kramer, Wickens, &

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Jake Fairnie, Centre for Research in Autism and Education, University College London Institute of Education; Brian C. J. Moore, Department of Psychology, University of Cambridge; Anna Remington, Centre for Research in Autism and Education, University College London Institute of Education.

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Correspondence concerning this article should be addressed to Anna Remington, Centre for Research in Autism and Education, University College London Institute of Education, 55–59 Gordon Square, London WC1N 0NU, United Kingdom. E-mail: a.remington@ioe.ac.uk

Donchin, 1983; white noise detection, Parks, Hilimire, & Corballis, 2009).

In contrast, Parks, Hilimire, and Corballis (2011) demonstrated that visual load had no effect on the amplitude of the electrophysiological response (event-related potentials [ERPs]) to task-irrelevant auditory stimuli. Similarly, two visual tracking studies failed to find any effect of task difficulty (the number of dimensions the participant was required to track) on the P3 amplitude (a late evoked response thought to reflect resource allocation) in response to a secondary auditory oddball task (Isreal et al., 1980; Wickens, Isreal, & Donchin, 1977). None of these studies assessed the effects of *auditory* load on auditory sensitivity to secondary stimuli.

Auditory Load Manipulations

Indirect evidence for the applicability of load theory in the auditory domain may be gleaned from studies that have systematically varied the presentation rates of auditory stimuli (via manipulation of the interstimulus interval [ISI])---which could be considered akin to a manipulation of perceptual load. Woldorff, Hackley, and Hillyard (1991) and Neelon, Williams, and Garell (2011) found that ERP responses to an oddball auditory stimulus in the unattended ear were attenuated when the rate of presentation to the attended ear was increased. These studies suggest that the unattended stimuli were processed to a lesser extent at high presentation rates. This is consistent with load theory, since increasing task-relevant auditory processing demands will reduce the processing of additional irrelevant auditory stimuli. However, as with the cross-modal literature, there are also conflicting reports, with other studies (Gomes, Barrett, Duff, Barnhardt, & Ritter, 2008) failing to find that faster presentation of attended stimuli led to a reduction in the processing of unattended stimuli. It is, however, difficult to draw any firm conclusions based on ISI manipulations because research on auditory scene analysis (Bregman, 1990) has shown that presenting a series of auditory stimuli with shorter ISIs can enhance the process of perceptual segregation, thus potentially confounding results with coincidental changes in the strength of perceptual segregation. Thus, there is not yet a consensus regarding the impact of manipulating stimulus presentation rates on auditory processing of unattended stimuli.

In research that is more similar to the present study, two studies based purely in the auditory domain have shown that unexpected auditory stimuli often go unnoticed when attention is engaged elsewhere. For example, a clarinet tone among spoken letter strings (Mack & Rock, 1998) was not detected when participants were asked to detect and memorize a target letter string, and the phrase "I am a gorilla" in a natural auditory scene (Dalton & Fraenkel, 2012) was not detected when participants were asked to listen to a conversation between characters preparing for a party in order to answer subsequent questions. However, neither of these studies systematically varied perceptual load. In one of the most promising demonstrations to date that load theory operates in the auditory domain, Francis (2010) manipulated auditory load and assessed the impact on interference produced by a simultaneous auditory distractor. Participants were presented with two voices, separated spatially or by gender, and were instructed which was to be attended (target) and which to be ignored (distractor). The task involved responding when the word said by the target talker possessed certain properties (e.g., pitch, modulation). The word uttered by the distractor talker was either congruent [sharing the same feature(s)] or incongruent with the target word. Francis found that interference from incongruent distractor words was greater in the low auditory load condition (target identified by single feature, e.g., pitch) than in the high auditory load condition (target identified by conjunction of features, e.g., pitch and modulation). Similarly, a recent study by Chait, Ruff, Griffiths, and McAlpine (2012) examined the magnetoencephalography response to a task-irrelevant auditory stream and how this was affected by primary task demands in both visual and auditory modalities. Auditory cortical responses to the unattended stream were reduced by an increase in the attentional load required to perform the primary auditory task. Interestingly, the attentional load in the visual task had no effect on cortical processing of the auditory information. However, it is important to note that the load manipulation involved increased memory demands under high load (the task required participants to briefly memorize complex target features in the high but not low load condition). This complicates the interpretation of these findings in relation to the question of whether load theory holds in the auditory domain.

Unlike the work detailed above, recent behavioral studies by Murphy, Fraenkel, and Dalton (2013) failed to find a within-modality effect of load on the processing of auditory distractors (both in selective attention and inattentional deafness paradigms). In their tasks, participants were affected by auditory distractors and noticed the distracting auditory stimuli in both the high- and the low-load conditions. Thus, while there is some suggestion that load theory can apply in the auditory domain, the picture remains unclear.

A limitation of some previous studies is that they used indirect measures of perception (reaction times [RTs] and ERP data) and so it is difficult to know whether or not participants consciously perceived the secondary auditory stimuli under the different manipulations of attention in the primary task. Electrophysiological responses (Neelon et al., 2011; Parasuraman, 1980; Woldorff et al., 1991) and distractor interference effects (Murphy et al., 2013) could reflect unconscious processing of stimulus-response associations, and for inattentional deafness paradigms one cannot rule out rapid forgetting (where a stimulus was, in fact, perceived but was lost from consciousness prior to being questioned about its presence), since the awareness measure is taken after the response in the main task (Wolfe, 1999).

Given that previous research has tended to use indirect measures, it is important to examine directly the impact that auditory load has on the conscious awareness of secondary—but expected—stimuli. To address this, in the current study we developed a novel paradigm with primary and secondary tasks that were both auditory in nature. Consequently, we were able to assess directly the impact of auditory load in a primary task on the ability to perform a secondary auditory task. In line with findings from the visual domain, we predicted that sensitivity to a secondary auditory stimulus would decline as the auditory load of the primary task was increased.

Method

Participants

Twenty participants (aged 17 to 34 years ($M = 24$, $SD = 5$), 12 males) were recruited via advertisements placed on social networking websites and were paid for their participation.

Background Measures

Audiometric thresholds. All participants had their audiometric thresholds measured prior to taking part in the study. Following the procedure recommended by the British Society of Audiology (2004), audiometric air-conduction thresholds were measured for the left and right ears for octave-spaced frequencies from 250 to 8,000 Hz. A Kamplex Diagnostic Audiometer AD17 and Telephonics TDH39P headphones were used. All of the participants had normal hearing (Table 1), defined as audiometric thresholds equal to or better than 15 dB HL for all frequencies between 250 and 8,000 Hz in both ears.

Experiment 1

Experiment 1 involved the development of a dual-task paradigm where the primary task was an "auditory search" task and the secondary task was an auditory detection task. To achieve this, we created an auditory analog of the "visual search" task used in previous research to test load theory (Macdonald & Lavie, 2008).

Materials

Stimuli were presented using OpenSesame experimental software (version 2.8.3; Mathôt, Schreij, & Theeuwes, 2012) on a Dell Latitude 15 5000 series laptop computer (with built in Realtek soundcard, 48-kHz sample rate, 16-bit resolution), through Audio-Technica ATH-M30X Professional Monitor Headphones. Stimuli were created in Logic Pro 9 (Version 9.1.8). Sound samples were selected from *Apple Loops,* a library of prerecorded audio clips, and all were edited to have a duration of 100 ms (including a 10-ms fade in and a 10-ms fade out).

Table 1
Means (and Standard Deviations) of the Audiometric Thresholds for the Left and Right Ears of All Participants

Ear	Frequency (Hz)	Mean (*SD*) threshold (dB HL)
Left	250	10.8 (2.0)
	500	10.8 (1.8)
	1,000	9.8 (1.8)
	2,000	7.8 (2.6)
	4,000	6.8 (2.5)
	8,000	6.5 (3.3)
Right	250	11.0 (2.0)
	500	10.5 (2.2)
	1,000	9.8 (3.1)
	2,000	8.0 (2.5)
	4,000	6.8 (2.5)
	8,000	5.8 (1.8)

Note. $N = 20$.

Target sounds were a lion's roar or a dog's bark and nontarget sounds were other animal sounds (duck, chicken, cow, crow, and rooster). The temporal and spectral properties of the sounds were analyzed using Cooledit, 2000. A summary of these properties is given in Table 2. The sounds differed from one another in the overall frequency range of the spectrum (measured here as the lower and upper frequencies at which the spectrum level was −18 dB relative to the level at the peak of the spectrum), the position(s) of the main peaks in the spectrum, and the extent to which the waveform was periodic (repeating regularly as a function of time and evoking a pitch sensation) or irregular (evoking a noiselike sensation).

As in visual search tasks, these elements were separated in virtual auditory space, with target and nontarget sounds presented simultaneously but emanating from different positions located on an imaginary semicircle around the participant's head. The critical stimulus (conditional stimulus [CS], the sound used in the secondary task that was presented only on 50% of trials) was the sound of a car driving past the participant. The CS was presented at a greater eccentricity than the target and nontarget sounds, from one of five possible positions around the head (Figure 1). The auditory load of the primary search task was manipulated by changing the number of nontarget sounds that were presented concurrently with the target (set size). Four set sizes were used: one (just the target sound), two (target and 1 nontarget sound), four (target and 3 nontarget sounds) and six (target and 5 nontarget sounds). Pilot testing established that the sound parameters and set sizes were effective in eliciting a robust load effect (i.e., longer RTs and higher error rates as the auditory load increased).

In order to position the sounds in virtual auditory space, interaural amplitude differences (IAD), interaural time differences (ITD), and overall level were manipulated (see Figure 1). A sound directly in front of the listener (at 0° azimuth, Position C) reaches the left and the right ears at the same time and has the same level at the two ears. However, when the sound is located to the side it reaches one ear before it reaches the other ear, giving an ITD. The maximum ITD for a head of average size is about 0.69 ms for a sound at ±90° azimuth (directly to the left or right, Positions 1 and 6) (Moore, 2012). The IAD also increases with increasing azimuth away from 0, but the maximum IAD depends on frequency, being greater at high frequencies than at low frequencies (Moore, 2012). However, for simplicity, here the IADs did not vary with frequency but were applied to the entire stimulus. Note that this is not unnatural, since large IADs can occur at low frequencies for sounds that are close to the head. The combinations of ITD and IAD were chosen so that the most extreme values gave the impression of sounds located at ±90° azimuth (directly opposite the left or right ear), while intermediate ITDs and IADs led to intermediate impressions of location, as illustrated in Figure 1. The overall level of the primary sounds was 80 dB SPL. The CS was made to appear at a greater distance than the sounds for the primary task by decreasing the level of the CS by 6 dB relative to that for the primary sounds.

Procedure

Participants were asked to listen to the stimuli and indicate as fast as they could (using a key press) which target was present (dog's bark or lion's roar). It was emphasized that this was the

Table 2
Summary of the Spectral and Temporal Characteristics of the Target and Nontarget Stimuli, and the CS. The Columns Show, From Left to Right, the Identity of the Sound, the Lower and Upper Boundaries of the Spectrum, Measured at the −18-dB Points Relative to the Peak, the Frequencies of the Main Spectral Peaks, and the Degree of Periodicity

Sound	Frequency range between −18 dB points (Hz)	Main spectral peak(s) (Hz)	Periodicity
Target: lion roar	540–2,215	216; 540; 1,200	Noiselike
Target: dog bark	475–1,980	614	Somewhat periodic
Nontarget: crow	381–4,364	502; 1,103; 1,810	Moderately periodic
Nontarget: chicken	902–4,900	989; 2,710	Noiselike
Nontarget: cow	164–2,565	187; 341; 738; 1,064; 1,426	Periodic
Nontarget: duck	311–6,070	329; 1,878	Periodic
Nontarget: rooster	780–2,058	886; 1,810	Periodic, chirp
CS: car	96–300	114	Moderately periodic

Note. CS = conditional stimulus.

primary task and should be prioritized. They were also asked to listen out for the CS (the car sound) and following their main task response they were asked to report (via a key press) whether the CS was present or absent on that trial. The CS (onset concurrent with that of other stimuli) was presented on 50% of trials.

Accuracy and response times for each trial were recorded by the computer program. Subsequent comparison of CS detection rates at the various set sizes allowed the effect of auditory load on secondary task performance to be ascertained.

Seventy-two trials were run for each set size. These were presented as two blocks for each set size (in counterbalanced order), each block containing 36 trials of the same set size. After 16 practice trials (4 practice trials for each set size), participants completed the eight experimental blocks. They were allowed to take breaks between blocks if required.

After completing the experimental trials, participants performed a control block to ensure that they were able to detect the CS under conditions of full attention. The control block consisted of 64 trials in which participants were told not to listen for a target (bark or roar) but simply to indicate the presence or absence of the CS (the sound of the car). There were 16 trials for each set size (50% containing the CS) in this control block. This was vital to confirm

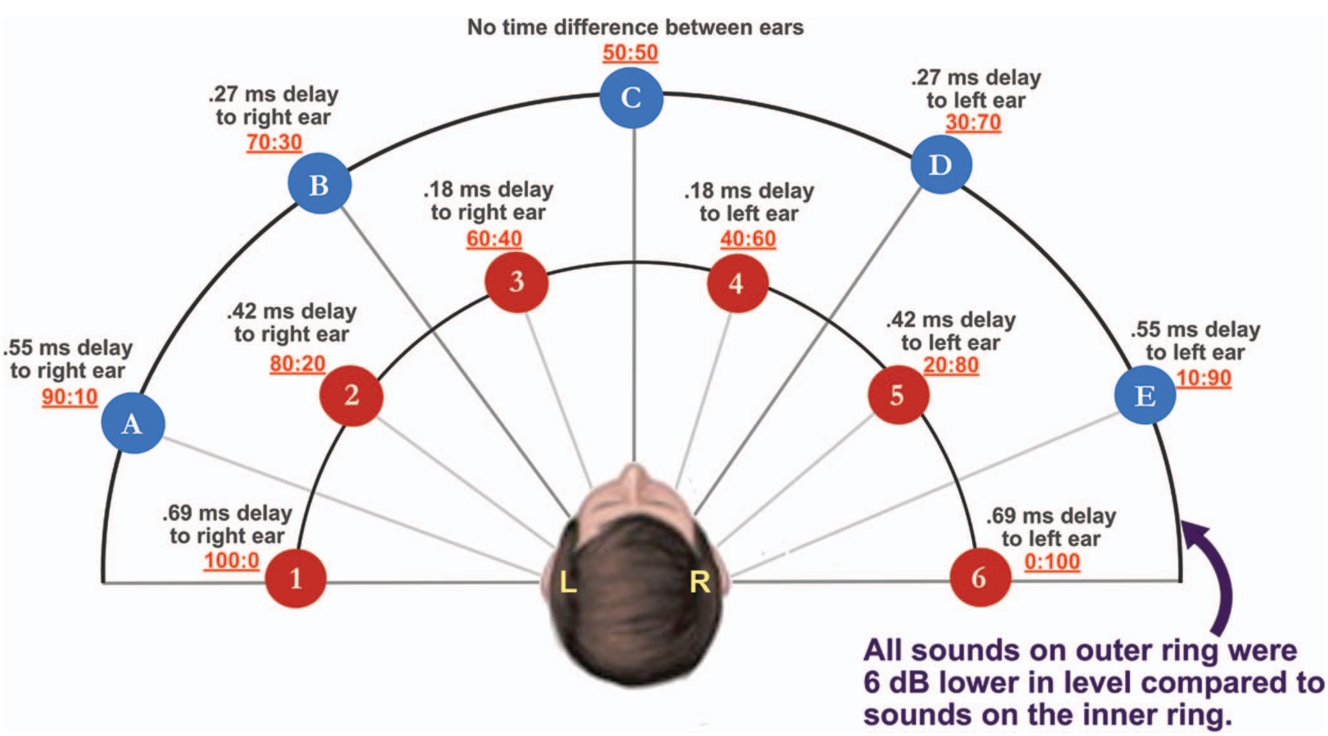

Figure 1. Interaural time differences (gray text), interaural amplitude differences (underlined text indicating the relative amplitudes at the left and right ears) and relative levels for the experimental stimuli in Experiment 1. Red circles with numbers indicate possible positions for the target and nontarget auditory stimuli, while blue circles with letters indicate possible positions for the conditional stimulus. See the online article for the color version of this figure.

that any failures to detect the CS during the experimental trials were due to the auditory load of the central task and not an underlying inability to perceive the CS.

Results

Primary task. Trials in which the response on the primary task was incorrect and those in which the RT was greater than 1.5 s were excluded from subsequent analyses for all of the experiments reported. Repeated-measures analyses of variance (ANOVA) were conducted on mean search RT and percentage errors with set size (load) as a within-subjects factor. There were significant main effects of set size for both RTs and error rates: participants were slower ($F(3, 57) = 17.456$, $p < .01$, $\eta_p^2 = 0.479$), and made more mistakes ($F(3, 57) = 12.714$, $p < 0\ .01$, $\eta_p^2 = 0.401$) as set size increased. This confirmed that our manipulation of set size was effective in increasing the auditory load of the task (Table 3). The progressive increase in error rates suggests that even under moderate levels of load, the task taxed processing resources. Note, however, that even at Set Size 6, the accuracy rates remained very high (84% accurate) and therefore do not suggest that capacity was entirely exhausted. This is comparable to the finding of Macdonald and Lavie (2008) that accuracy was 89% in the high-load condition.

CS detection task. Trials on which responses were incorrect for the primary task were excluded from the detection analyses. Detection sensitivity, which takes into account hits and false alarms to give a true measure of sensitivity, was calculated for each participant at each set size (Table 4). Because the hits and false alarm rates were not normally distributed, we calculated A (a corrected version of a'; Zhang & Mueller, 2005), the nonparametric equivalent of d'. Note that A takes values between zero and one, where 0.5 typically indicates that signal cannot be distinguished from noise and one indicates perfect detection (Stanislaw & Todorov, 1999). A repeated-measures ANOVA with set size as the within-subject factor revealed a significant main effect of sensitivity ($F(3, 57) = 42.305$, $p < .01$, $\eta_p^2 = 0.690$). Sensitivity decreased with increasing auditory load (shown in Figure 2B). A repeated-measures ANOVA on response criterion (β) with set size as the within-subject factor revealed no significant effect of set size ($F < 1$).

Control block. All participants detected the presence of the CS at 88% or higher for all set sizes. Crucially, CS detection in the control block did not differ between Set Size 1 (*M* detection rate = 95.6%), Set Size 2 (*M* detection rate = 96.6%), Set Size 4 (*M* detection rate = 97.5%) and Set Size 6 (*M* detection rate = 95.3%; $F < 1$), showing that the CS was easily and equally detected in all load conditions when there was no primary search task to perform.

Table 3
Mean RTs and Error Rates for the Primary Task for Each Set Size (With SDs in Parentheses)

	Set size			
	1	2	4	6
RT (ms)	924 (194)	1081 (222)	1088 (215)	1159 (247)
Percentage error	4.3 (.05)	9.9 (.09)	15.2 (.11)	16.3 (.13)

Note. RT = reaction time.

Table 4
Results for Conditional Stimulus Detection, Showing Detection Sensitivity (A), and Criterion (β) For Each Set Size

	Set size			
	1	2	4	6
Detection sensitivity (A)	.94	.90	.86	.79
β	1.97	1.87	1.62	1.73

This was vital to ensure that the CS was not treated as an additional nontarget item in the array. On the control block, participants were told not to perform the primary task (target identification) but to focus solely on detecting the CS under the various levels of load. If the CS were perceived as an additional nontarget item, then we would expect to see detection sensitivity decline as the number of items in the array increased (despite participants being told to ignore them). The fact that this was not the case confirms that the CS was a clearly separable item, and was not grouped with the elements in the search array.

Experiment 2

Spatial Location Tasks

In Experiment 1 we created an auditory search task with spatially separated sounds that was analogous to those used in the visual domain to assess selective attention under varying levels of load. Because our soundscape was created using an artificial manipulation of ITDs and IADs, a legitimate concern was whether the various sounds were actually *perceived* as coming from separate locations. To confirm that participants perceived the intended differences in spatial location, discrimination and identification

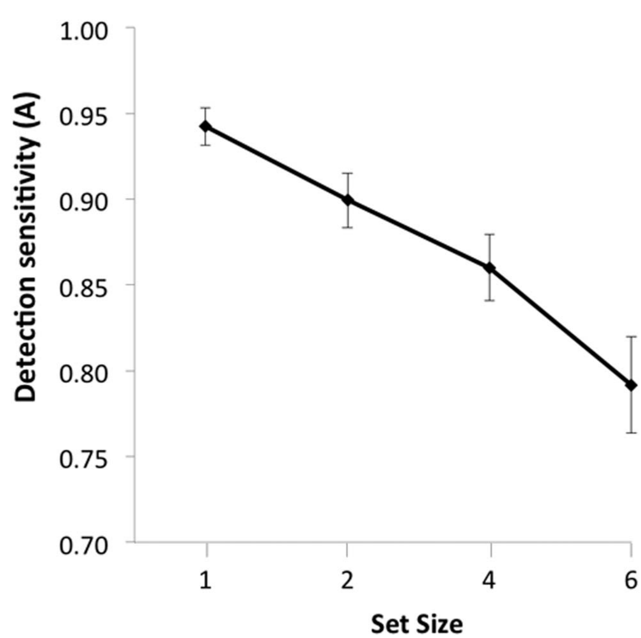

Figure 2. Detection sensitivity (A) for each value of auditory load. Error bars show ±1 standard error of the mean.

tasks were developed. Stimuli were created and presented using the software and hardware detailed for Experiment 1.

Experiment 2a. Location Equivalence Task

Participants were shown a map of the six possible locations for the target sound (Figure 3) and then presented with two consecutive sounds (both 100 ms, dog bark) that were either in the same location (15 trials; *1–1, 2–2, 3–3, 4–4, 5–5, 6–6, 1–1, 2–2, 3–3, 4–4, 5–5, 6–6, 1–1, 4–4, 6–6*) or different locations (15 trials; *1–2, 1–3, 1–4, 1–5, 1–6, 2–3, 2–4, 2–5, 2–6, 3–4, 3–5, 3–6, 4–5, 4–6, 5–6*). Participants were asked to indicate with a key press whether the sounds came from the same or different locations. Trial order was randomized and correct-answer feedback followed each trial.

Experiment 2b. Proximity Discrimination Task

Participants were shown a map of 16 possible locations from which sounds could emanate (Figure 4) and were then presented with two consecutive sounds that varied in their intended distance from the participant (dog bark in a position selected from Positions 1–6 followed by car sound in one of the inner or outer CS positions). Participants were asked to indicate with a key press whether the second sound was nearer or further away than the first sound. Ten trials were presented in random order (*1-A, 1-F, 6-J, 6-E, 4-H, 4-C, 5-G, 5-B, 6-A, 2-J*).

Experiment 2c. Location Identification Task

Participants were again shown a map of possible locations (Figure 5) and then presented with a sound (either a 100-ms dog bark or a 100-ms car sound). Participants were asked to indicate where the sound was located by using the number and letter keys corresponding to the various locations. The bark was presented in each numbered location twice, and the car was presented in each lettered location twice. Trial order was randomized. Feedback (a correct or incorrect error tone) was given after each trial, followed by an image displaying the correct location.

Results

The results showed that participants were able to perceive the items as coming from different spatial locations (Experiment 2a) and different eccentricities (Experiment 2b) and that they were able to identify the location (Experiment 2c) to a high level (Table 5).

Discussion

Our findings demonstrate that increased auditory perceptual load reduced the conscious perception of a secondary auditory stimulus. Specifically, the ability to detect a sound (the CS) that was not presented on every trial was consistently poorer when performing an "auditory search task" with a large array (high load) than with a small array (low load) of nontarget elements. Crucially, when participants no longer needed to perform the primary task they were able to detect the CS with over 95% accuracy under all array sizes of the primary sounds, indicating that the failure to perceive the CS under high perceptual load reflected the allocation of attention, rather than an inability to identify or respond to the CS.

The present study, therefore, provides compelling support for the applicability of load theory in the auditory domain. As with vision, it seems that there is a finite auditory perceptual capacity that is assigned in an automatic fashion until resources are exhausted. Additional processing of distractors, or secondary task performance, therefore depends on whether any spare capacity remains after resources are assigned to task-relevant processing. The observation that load theory applies to audition is in line with the theoretical predictions of the framework. Its original development was, in part, based on early dichotic listening experiments where the fate of unattended stimuli appeared to depend on the amount of information presented to the attended channel (Lavie, 1995; Lavie & Tsal, 1994). However, this extension of load theory from the visual to the auditory domain is not entirely intuitive. The two systems are inherently different. Hearing is our early warning system: we survive by detecting threats in our environment, and these threats tend to be heard before they are seen, due to our 360°

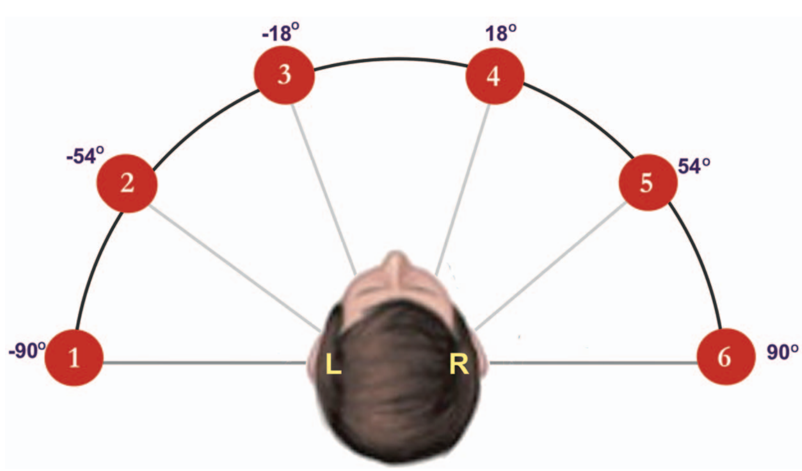

Figure 3. Birds-eye view schematic diagram of intended sound locations for the location discrimination task. See the online article for the color version of this figure.

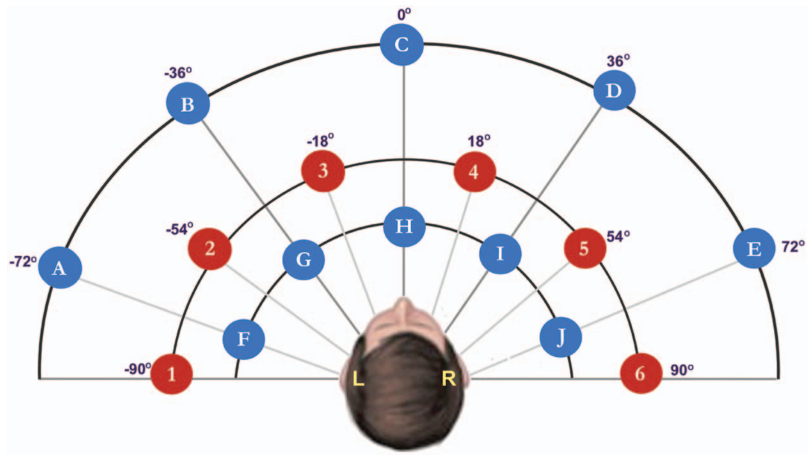

Figure 4. Schematic diagram of intended locations of the dog sound (red numbered positions) and car sound (blue lettered positions). See the online article for the color version of this figure.

auditory perceptual ability compared with a limited field of vision. Noticing such threats depends upon the ability to perceive items that may not be related to the task we are pursuing at the time. This will, in some cases, be due to the physical properties of the stimuli that set them apart from others (e.g., very loud sounds will typically capture attention), but in many cases a number of sounds will also enter awareness based on their function (e.g., greetings, door bells, and telephone rings). It is interesting, therefore, that in our experimental setup the perception of the CS was dependent on the auditory perceptual load imposed by the primary task. Thus, an important question for future research is whether meaningful sounds (such as alarms and vehicle horns) are subject to the same capacity limits.

How Do Our Findings Fit With the Previous Literature?

As outlined above, to our knowledge, there are very few studies that have examined the effect of auditory load on auditory detection of a secondary stimulus over multiple trials. Of the three that did, two provided evidence consistent with load theory (Chait et al., 2012; Francis, 2010) and one did not, with similar effects of distracting (irrelevant) stimulus at all levels of load (Murphy et al., 2013). It is possible that differences in the method of presentation can account for the disparity. Murphy et al. (2013) interleaved the distractor with the target items with only partial overlap, rather than presenting the distractor simultaneously with any one target item. Consequently, there would have been periods when only the distractor was being played, which may have led to its processing even on trials with high perceptual load. In addition, it may have been the case that the level of load was low in all conditions. The authors themselves remarked on this concern after their first experiment, and they conducted a second version with reduced ISI to increase the overall load of the task. A potential confound in the auditory domain is that shortening the ISI can *facilitate* segregation of an auditory stream (Bregman, 1990). This would result in an overestimation of the load level in all conditions and would

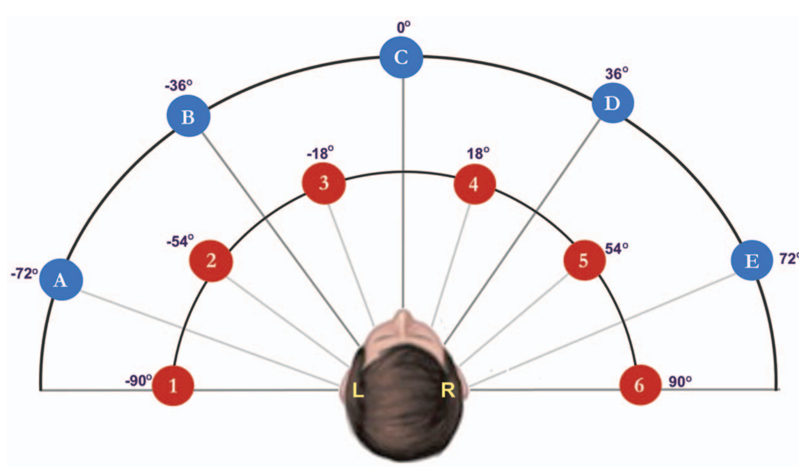

Figure 5. Birds-eye view schematic diagram of possible locations for sounds. See the online article for the color version of this figure.

Table 5
Mean Percent Correct Scores and SDs for Same-Different Localization (Experiment 2a), Discrimination of Distance (Experiment 2b), and Identification of Sound Location (Experiment 2c)

	Experiment 2a: same or different location	Experiment 2b: near or far discrimination	Experiment 2c: identify location
Mean (%)	91	88	67
SD (%)	10	12	14

Note. Chance level was 50% for Experiments 2a and 2b, but 18% for Experiment 2c.

perhaps explain the impact of auditory distractors at all load levels seen in the study of Murphy et al. As briefly reviewed in the introduction, our paradigm builds on previous research by employing a direct measure of conscious awareness rather than by assessing indirect distraction effects (Francis, 2010; Murphy et al., 2013) and by removing differences in working memory demands between high and low load conditions (Chait et al., 2012; Francis, 2010).

Development of a Novel Paradigm

Our study offers a new paradigm that enables the systematic exploration of perceptual capacity in the auditory domain. The auditory search task developed here is, to our knowledge, the first auditory analog of the commonly used "visual search task." It allows the presentation of concurrent but spatially separated sounds to the listener, who is asked to identify a target sound from among nontarget elements, while also listening out for a more distinct CS sound. A very short presentation time (100 ms) was employed to preclude the voluntary shifting of auditory attention and therefore avoid a serial processing strategy. It is possible, however, that participants performed a serial search of the echoic memory of the stimuli (Darwin, Turvey, & Crowder, 1972). Nonetheless, all items would have to be encoded simultaneously at the time of presentation, and we therefore believe that, despite this possibility, the task offers a measure of auditory perceptual capacity. One direction for future research would be to reduce the possibility of serial search by using an auditory mask (a burst of noise that has the same long-term average spectrum as the stimuli) immediately after the presentation of the stimuli.

The results of Experiment 2 confirmed that the sounds were indeed perceived as emanating from different locations, both with respect to angle and distance from the head. The array size, location of sounds, and CS presentation can all be varied, such that a full examination of the effect of various factors on selective attention can be conducted. For example, in addition to assessing the effects of auditory load, it is possible to investigate the effects of target-distractor similarity, target meaningfulness, and perceived separation between elements. As such, this paradigm may be a useful tool in auditory attention research—as the visual search task has been when investigating visual processing.

It is interesting to note that even at the lowest set size, RTs were longer than equivalent measures in the visual domain (an average of over 900 ms vs. 600 ms in visual search tasks; see Macdonald & Lavie, 2008). This delay may arise from the need to translate from the auditory modality into a key press. Anecdotally, we observed that participants often looked down to check which key to press before making their response. This could be checked by employing a modified version of the task where participants would give oral responses. In addition, using the auditory mask (mentioned above) after presentation of the array would reduce memory-related components that may become involved in the task when a delay exists between stimulus presentation and response.

Implications

Our demonstration that people are more likely to be "deaf" to a sound when engaged in a task with a high auditory load has a number of practical implications. It indicates the need to be aware of the consequences of performing high load tasks in daily life. For example, when concentrating on a radio program while driving, one may fail to hear other important sounds such as an approaching ambulance. When eavesdropping on a conversation between two strangers on a train you might fail to hear your station stop being announced. The development of safety recommendations should therefore take the level of auditory load involved into consideration.

The concept of load theory in the auditory domain may also inform our understanding of listening effort (defined as the additional allocation of cognitive resources to help performance of a challenging auditory task; Hicks & Tharpe, 2002). While a full discussion of this body of literature is beyond the scope of this paper, there are undoubtedly parallels between listening effort and perceptual load. Task performance in the presence of background noise is worse (and more effortful) than when sounds exist in isolation (McGarrigle et al., 2014; Sarampalis, Kalluri, Edwards, & Hafter, 2009). Recognizing the factors involved in listening effort is important to help improve the effectiveness of hearing aids that address problems with comprehension of speech in noise and to ameliorate age-related hearing decline.

Understanding situations when we are more or less susceptible to auditory distraction also has implications for clinical populations where resistance to distraction appears to be altered. For example, our paradigm could be used to assess auditory selective attention and perceptual capacity in individuals with attention deficit hyperactivity disorder (Kofler, Rapport, Bolden, Sarver, & Raiker, 2010) and autism (e.g., Remington, Swettenham, Campbell, & Coleman, 2009). In the latter, for example, anecdotal reports indicate that individuals often find seemingly innocuous sounds very distressing, and report being overwhelmed by competing sounds. It is clearly of great importance to characterize this altered auditory processing and to seek to minimize any difficulties.

In conclusion, we developed a novel paradigm that allowed us to systematically assess the impact of auditory load manipulations on conscious awareness of additional auditory stimuli. By addressing the methodological issues of previous research, the present study aimed to clarify the conflicting reports of within-modality effects of auditory load on auditory perception. Our results indicate that load theory is applicable in the auditory domain.

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