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When the Siren Sounds: In Search of Acoustic Properties that make an Alarm Signal Effective at Capturing Attention

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Foreword

I want to thank Robin Liljenberg for helping me with the data collection. I also want to thank John Marsh for his help in this study.

Abstract

A functional and effective alarm signal is a critical component of alarm systems designed to alert workers of impending danger. In a previous study (Hansson, 2017) background alarm sirens composed of changing-state sounds with an embedded temporal deviant, produced greater disruption of serial short-term memory than a signal without a deviant. However, to give rise to disruption the siren needed to change from fast to slow, since a change from slow to fast was impotent in its effect on task performance. In the current study, whether acoustic change was a necessary prerequisite for obtaining the fast-to-slow deviant effect was explored. Thus, repeated tones—steady-state sequences—presented at slow or fast rates were used with or without a temporal deviant (change from slow-to-fast vs. change from fast-to-slow). In the context of the steady-state sequences, both slow-to-fast and fast-to-slow temporal deviants produced disruption relative to the fast and slow control sequences. This suggests that a changing-state sequence is required for the fast-to-slow temporal deviant effect to arise. However, an alternative explanation based upon inter-stimulus intervals is also entertained. Understanding the acoustic parameters of sound is necessary to develop alarms sirens that are better at capturing attention. The current study suggests that embedding temporal deviants within sirens can promote greater attentional capture, but that this may depend on the nature of the alarm signal (whether it is changing *vs*. steady-state) and the direction of the change of speed (slow-to-fast *vs*. fast-to-slow).

Keywords: Alarm sirens; Steady-state; Changing-state; Temporal deviant; Orienting response.

Innehåll

Introduction

Research has demonstrated that task-irrelevant background sounds impact negatively upon human cognitive performance (Miles, Jones, & Madden, 1991; Wood & Cowan, 1995; Hughes, Vachon, Jones, 2007). For example, Cherry (1953) showed with the so-called cocktail effect that even low intensity sounds could grab attention, especially if the sound stream contained the participant's own name. The presence of to-be-ignored sounds impair human cognitive performance in a variety of tasks. This is the so-called "irrelevant sound effect" (Miles, Jones, & Madden, 1991; Beaman, 2004; Knez & Hygge, 2002: Röer, Bell, & Buchner, 2013). Some to-be-ignored sounds convey urgency (Noyes, Hellier & Edworthy, 2006). The perceived urgency of a sound is affected by its acoustic parameters such as its frequency, speed, pitch range and amplitude (Edworthy, Loxley & Dennis, 1991; Hellier, Edworthy, Weedon, Walters, & Adams, 2002).

The disruptive effect of sound on cognition can be observed via the orienting response. Unexpected sound or deviant sounds capture attention as they provoke an orienting response (Sanmiguel, Linden, & Escera, 2010). The orienting response is an automatic reflex that humans and animals possess. This reflex is useful, when hearing unexpected sounds that need to be analysed to see if they convey danger or potential benefit (Potter, Lynch, & Kraus, 2015). When an orienting response is provoked in organisms, it is typically indexed by the organism turning in the direction of the sound. The orienting response is also associated with physiological changes such as slowed heart rate, pupil dilations and so on (Brandt, 2011; Potter et al., 2015). The orienting response to deviant sounds has been vigorously tested in the "auditory oddball paradigm", wherein a rare, deviant sound is presented within the context of a repeated standard sound. This produces an orienting response that can be measured with electroencephalography (EEG) through a triumvirate of components (P3a, MNN and RON). Within the task, the orienting response can also be measured by pupilometry: the onset of a deviant produces pupil dilation (Schröger & Wolf, 1998a; Schröger & Wolf, 1998b).

Today alarm devices are embedded in most electronics within our technological world. Machinery within cell phones and power-plants have different alarm signals embedded within them. The goal of an alarm signal is to capture human attention. Alarm signals can comprise messages, cell phone notifications or the alarm sirens of emergency vehicles (Ljungberg et al., 2012). If the alarm systems are not reliable (e.g. such as when a signal sounds when no danger is present), receivers may not pay attention to the alarm when the signal is true, this is called the cry wolf effect (Bliss, Washington & Fuller, 1994; Breznitz, 1983).

When an alarm signal sounds when there is no danger the receiving humans learn not to respond to that signal. Then when a true alarm signal sounds, humans do not check the alarm and ensuing accident, or disasters can follow. What can also happen is that humans respond slower or less frequently to an alarm signal that sound false alarms. Bliss et al.(1994) showed that if the conceived urgency of alarm signals were increased, participant's response times to alarms were faster. Therefore, it is important to develop better alarm signals that can give the right urgency for the right situation.

As Cherry (1953) showed, humans have a selective attention system that enables them to focus on the task at hand, and filter out irrelevant stimuli. Humans also have the ability to detect irregular, unexpected stimuli, and if necessary, act on them (Sokolov, 1963; Schröger, 1996). The problem is that when the brain switches from selective attention and irregularity detection, it be distracted from the main task (Parmentier, 2016). This is especially the case when the to-be-ignored sound conveys a repeated pattern (e.g. AAAAA), and then the onset of a deviant (e.g. AAABAAA). When this occurs, the orienting response can "kick in". The individual's attention is captured by the deviant sound and subsequently must return to the focal task (Escera, Alho, Winkler, & Näätänen, 1998; Andrés, Parmentier, & Escera, 2006). However, not all sound captures attention. Changing-state sound that conveys no auditory deviant can impair short-term memory for sequences of visually-presented items. This is called the changing-state effect (Jones & Macken, 1993). Two theories have been suggested as to why deviant and changing sequences (AFGHB) disrupt task performance.

The first theory is termed the uni (single) mechanism theory. This states that attentional capture happens for each change (A F G H B) within a changing-state sequence. Each time the auditory signal changes, an attentional switch occurs (Wood & Cowan, 1995). Thus, according to the uni-mechanism theory, the auditory deviant effect and the changing-state effect are underpinned by the same mechanism. The second theory that opposes the first, is the duplex mechanism account (Hughes, 2014). This states that two distinct forms of distraction exist. On this account, attentional capture does not happen for each of the changes within a sequence (A F G H B). Instead, the disruption that changing-state sound confers on serial short-term memory is attributable to *interference-by-process*. This supposes that the disruption of serial short-term memory is attributable to a clash of two similar processes. The first is applied automatically and preattentively to the sound and processes the order of acoustic changes within the sound. The second is the deliberate process of serially rehearsing the visually-presented to-be-recalled items via subvocal/inner speech. The duplex mechanism account holds that the deviant effect is different to the changing-state effect in that it is attributable to attentional capture. Here, a deviant item among otherwise similar items (e.g., (e.g., an item presented in a different voice; the red item in the following example: A F G I H B) captures attention from the focal task and gives rise to disruption (Hughes, Vachon, Jones, 2007). Steady-state, repeating sounds (AAAAAA) typically fail to disrupt performance (Campbell, Beaman & Berry, 2002; Jones & Macken 1993) unless they contain a changing-state element e.g. AAAaAA (whereby the small a represents a change in voice).

In relation to the design of effective alarm signals, deviant sounds have shown in research (Parmentier, 2016; Berti & Schröger, 2003) to give rise to longer response times and less accurate responses in the main task, suggesting that deviant sounds are good at capturing attention away from that task as indexed by behavioural distraction and an orienting response. Orienting responses have been shown for sound streams that are perceived as approaching, rather than receding, from the perceiver. That is, orienting responses associated with “looming” occur whereby a sound signal increases in volume (Bach et al., 2008). A phenomenon associated with looming is the Doppler shift. The Doppler shift refers to the change in sounds that occur as a sound-emitting object approaches or as one moves toward or away from that sound source. For example, the pitch of a siren from an emergency vehicle sounds higher when the siren comes towards the receiver, and drops in pitch when the siren arrives and passes the receiver. Similarly, moving toward the sound source results in a change in the frequency of the siren. More sound waves per unit time are experienced as one approaches the sound emitting object, and therefore the speed of the siren is faster.

In my previous study (Hansson, 2017), I embedded a deviant within a stream of to-be-ignored siren sounds in the context of a serial short-term memory task. The deviant was a change in the speed of the siren. Either the siren started slow and changed to fast, or it started fast and changed to slow. Compared against fast and slow sequences without a deviant, the change from fast to slow produced disruption of serial short-term memory, but the change from slow to fast did not. At first glance this finding is at odds with what might be expected from the literature on looming in relation to the Doppler shift. Looming sounds produce an orienting response and so it might have been expected that a siren sound that changes from slow to fast—that might give the impression of approaching a sound emitting object—would produce more disruption that a siren sound that changes from fast to slow that might give the impression of moving away from the sound source. In fact only the siren that changed from fast to slow produced attentional capture as measured by impairment of task performance. Clearly such an unexpected result requires some further consideration and the acoustic parameters underpinning the effect need further scrutiny.

The goal of the current study was to determine whether the siren has to change-in-state in order for the fast-to-slow deviation to be more attention-capturing than the slow-to-fast deviation (that was impotent in capturing attention in Hansson et al., 2017). In order to investigate whether this was the case, the disruptive potency of steady-state siren sounds that either increased or decreased in speech was considered. Since the siren sounds in Hansson et al. contained no inter-stimulus interval, it was necessary to introduce such an interval otherwise the steady-state, repeated siren, would have been continuous.

Hypothesis

As the above research has shown, deviant sounds capture attention whereas changing-state sounds do not. Changing-state sounds disrupt performance more than steady-state sounds but this is due to an interference-by-process, not attentional capture (Hughes et al., 2007). Steady-state sounds comprising a deviant, however, should capture attention (Hughes et al., 2007). In my previous study (Hansson, 2017), I showed that alarm sirens composed of changing state sounds with an embedded temporal deviant whereby the siren went from fast to slow produced more disruption than fast and slow sirens without a deviant and sequences conveying a slow-fast deviant. In the present study, the acoustic parameters involved in capturing attention are studied. Specifically, I address whether a temporal deviant embedded in steady-state sequences have the propensity to capture attention and furthermore whether there is greater disruption from a steady-state sequence conveying a fast-to-slow temporal deviant than one conveying a slow-to-fast temporal deviant. I hypothesised that the presence of a temporal deviant should impair serial short-term memory performance, regardless of whether it is implemented as slow-to-fast, or fast-to-slow. Moreover, I hypothesised that if the temporal deviant is related to the changing nature of the siren, that different results should be obtained here, as compared to Hansson (2017). Specifically, the asymmetry between the disruptive potency of fast-to-slow as compared to slow-to-fast deviants should not be observed.

Method

Participants

44 participants were recruited for the study. All reported normal hearing and normal or corrected-to-normal vision. Recruitment was by TimeCenter and random drop-ins. In return for participating in the study, participants were rewarded with two cinema tickets.

Apparatus and Materials

The experiment was executed on a PC running an E-Prime 2.0 program (Psychology Software Tools) that controlled stimulus presentation. To be remembered items consisted of the random presentation of eight digits from the set, 1-8 digits on a computer screen. No digit could be presented twice in a given list. Each digit was shown for 350 ms with a 400 ms ISI. Participants wore headphones throughout the study and the to-be-ignored alarm siren sounds were presented over headphones at approximately 65dB(A). The alarm sirens consisted of one steady state tone at 300 Hz sampled with a 16-bit resolution at a sampling rate of 44.1 kHz using *Sound Forge 8*. The sirens either contained a deviant, or did not. Deviants were represented as a temporal change, either going from fast-to-slow or from slow-to-fast. The speed of the tones was manipulated by the length of the tone, rather than the length of the ISI with tones either presented for 200ms with 200ms ISI in the fast condition, or 600ms with 200ms ISI in the slow condition. The four types of sound stimuli are as follows:

a) Fast – tones presented at 200ms each with 200ms ISIs throughout the trial.

b) Slow – tones presented at 600ms each with 200ms ISIs throughout the trial.
c) Fast-slow deviation – tones started at 200ms each with 200 ms ISIs between as a "standard" then between the presentation of the fourth and fifth visual item, deviated to 600ms each, remaining at the slow speed for the rest of the trial and the subsequent trials until the next deviation.
d) Slow-fast deviation – tones started at 600ms each with 200ms ISIs as a "standard" then between presentations of the fourth and fifth visual item, deviated to 200ms each, remaining at the fast speed for the rest of the trial and the subsequent trials until the next deviation.

Experimental Design

A 4 [2 (Sound Speed) x 2 (Deviant)] design was used whereby sound speed (fast *vs.* slow) and presence of a deviant (deviant *vs*. no deviant) was manipulated within-participants. The study was conducted in a classroom in the University of Gävle. Participants wore headphones and were presented with to-be-ignored sound across these. The participants were then presented with steady state sounds with, or without a deviant. The deviant was temporal in nature such that the sequence either changed from fast to slow, or from slow to fast. Participants performed 90 trials. The previous signal acted as standard until the next signal occurred. Deviant trials were presented randomly within the 90 overall trials with the constraint of ensuring that there were at least four non-deviation trials between each deviation. There were seven of each deviation trial throughout the study. Serial recall performance was the dependent variable. Participants were required to remember the correct order of the eight randomly presented digits on each of the 90 trial's.

Procedure

The participants were tested in groups wherein they were instructed to sit in front of a laptop computer screen while wearing headphones. Digits sustained a visual angle of about 2.6^{o} (participants sat at approximately 50 cm distance from the screen). They were instructed to ignore sounds coming from their headphones. They also received written instructions on their computer screens about the test. Following presentation of the last to-be-remembered item in a sequence, the digits were re-presented at random positions within a circular array. Beneath the array there were eight horizontally arranged response boxes corresponding to each position in the to-be-remembered list. Participants were required to reproduce the to-be-remembered list in forward serial order by selecting the digits using the mouse-driven pointer. Once a digit was selected, it disappeared for 50 ms before reappearing and a copy of the digit appeared in the response window corresponding to the current recall position. Because items remained in the circular array once selected, repetitions of the same item were possible, as with written recall.

Before each trial started there was a 5.6 second introduction of the sounds throughout which six sets of dashes were presented (--), then an arrow (→) to signal the onset of the first visually-presented digits. The dashes had the same visual timings as the digits so that participants could become accustomed to the "standard" sound for the trial did not occur under different conditions than the presentation of the to-be-remembered information. Participants were given four practice trials (the sound corresponding with the speed of the first standard speed encountered in the study). Participants initiated the test themselves and it took approximately 40-50 minutes to complete. The test could be aborted if participants so desired.

Results

A strict serial recall scoring system was used whereby participants were required to put a digit in its correct original serial position to score a point. Figure 1 shows the mean serial recall performance in the four conditions collapsed across serial position. Deviant sound appears to decrease correct recall performance. Speed, however, did not appear to differentially disrupt performance. Moreover, the presence of a deviant had a similar effect regardless of whether it was embedded within a fast or slow "base sequence".

These observations were confirmed with a 2 (Sound Speed: Fast vs Slow) × 2 (Deviant: Deviant Present vs. Deviant Absent) repeated measures Analysis of Variance (ANOVA). This revealed no main effect of Sound speed, $F(1, 43) = .099$, $MSE = .002$, $p = .75$, η2p = .002. However, there was a main effect of Deviant, $F(1, 43) = 9.063$, $MSE = .004$, $p = .004$, η2p = .174, but this did not interact with Speed, $F(1, 43) = .423$, $MSE = .002$, $p = .519$, η2p = .010.

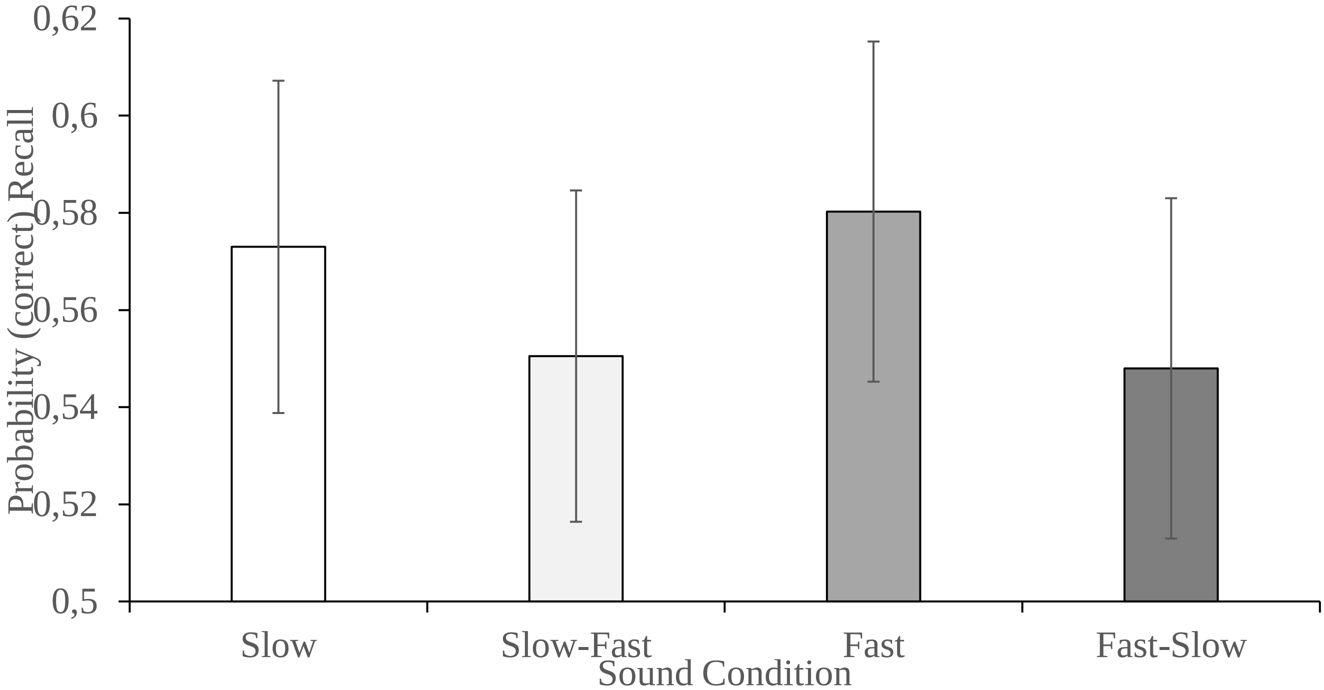

Figure 1. Probability correct recall, in the four conditions. The error bars refer to the standard deviation of the mean in each condition.

Discussion

Sound streams containing a deviant have been shown to impair serial recall performance compared to sequences with no deviant (Berti, & Schröger, 2003; Hughes, Vachon, & Jones, 2007; Röer, Bell, Marsh, & Buchner, 2015; Vachon, Labonté, & Marsh, 2017). Deviants capture attention which can be indexed by the orienting response, (e.g. head movement, pupil dilation, increased heart rate; Brandt, 2011; San Miguel, Linden, & Escera, 2010). In the context of alarm system design, information about the parameters of an auditory signal that captures attention could be used to develop more effective, attention-grabbing alarm sirens. In the current study, I attempted to explore the factors that led to greater attentional capture from a temporal deviant embedded within a siren in my previous study (Hansson, 2017). More specifically, the current study was undertaken in an attempt to understand why a change in the speed of a siren – going from fast-to-slow, elicited attentional capture, while the opposite pattern - going from slow-to-fast failed to produce any disruption (Hansson, 2017). Such a finding appears to be at odds with the so-called Doppler shift effect whereby looming sounds appear to get faster the nearer they approach an individual (the receiver) while a receding sound gets slower. This is why auditory looming sounds are thought to be more threatening than white noise (Mccarthy, & Olsen, 2016). Since auditory looming sounds produce a heightened orienting response (Bach et al., 2008), it could be expected that a siren changing from slow to fast should produce more attentional capture than a siren changing from fast-to-slow, but the opposite was true (Hansson, 2017).

To understand the fast-to-slow temporal deviant effect further, I examined acoustic parameters that could be responsible for producing the slow-fast deviant effect. In the current study I explored whether the presence of change within the siren signal could contribute to the effect. Thus, in the current study I presented participants with the same token repeated over. Since there was no ISI between alternating high and low frequency tones in my previous study I inserted an ISI between tones in the current study, otherwise the tone would have been presented continuously. To vary the speed of the siren, I inserted an ISI between successive tones. Speed was determined by ISI alone. The results of the current study demonstrated that a temporal deviant within a repeated tone sequence produced attentional capture regardless of whether the deviant was a change from slow-to-fast or from fast-to-slow presentation (cf. Hughes, Vachon, & Jones, 2007). Like my previous study, no main effect from speed (pure fast vs. pure slow sounds) was found. This pattern of data suggests that either 1) the attentional capture produced by the fast-to-slow deviant in my first study was somehow due to the presentation of alternating tones to create the siren sound, or 2) the addition of an ISI in the current study eliminates the fast-to-slow deviant effect. To address this possibility a further study will be undertaken in which the ISI’s used in the current study will be incorporated with the changing (alternating) tones used in my first study. If, the fast-to-slow deviant effect returns in this study, then it is necessary for a siren to acoustically change over time to capture attention. If, however, the fast-to-slow deviant effect is not replicated, then it is likely that the sounds must occur without temporal gaps between them in order to produce the effect. It is perhaps hasty to speculate on what the mechanism underpinning the fast-to-slow deviant effect might be, prior to replicating it. However, one possibility is that in the fast-to-slow condition of Hansson (2017) the perceptual system is expecting the arrival of a sound that is delayed, whereas in the slow-to-fast condition, the stimulus arrives but is shorter than expected. Although speculative, maybe the absence of an expected event is more distracting that the truncation of that event.

While I have mentioned auditory looming and the Doppler shift effect in the context of the fast-to-slow deviant effect, caution is required in doing so. The auditory looming effect is most readily perceived when sound intensity rises (Bach et al., 2008): Rising sounds are more perceptually salient, than receding sounds and invoke an orienting reflex. Sounds did not in the current study, nor that in Hansson (2017), change in intensity. Moreover, in the case of Doppler shift, sounds that approach the receiver get lower in pitch. Again, this was not an acoustic manipulation adopted for the siren signals in my first study (Hansson, 2017). The only acoustic parameter that mimicked the Doppler shift was the change in the temporal frequency of the tones going from slow-to-fast within the slow-to-fast condition, but this did not produce any disruption compared to the opposite. Other factors, related to one another that are thought to be also related to the speed of alarm signal presentation, are perceived urgency and arousal. Hellier, Edworthy, Weedon, Walters, and Adams, (2002) suggest that fast sounds promote more arousal and perception of urgency than slower sounds. Therefore, an alarm signal that changes from slow-to-fast should produce more arousal and perceived urgency at that change, than a signal that changes from fast to slow. However, if arousal and perceived urgency dictated distraction then greater disruption should be observed in the slow-to-fast condition than the fast-to-slow condition which does not correspond to the behavioural pattern of data in the current study, nor that of Hansson (2017).

Understanding the acoustic properties of sounds that capture attention can be used to develop better attention-grabbing alarm sirens. This an important issue in our continually growing litigious and hazard-aware society. Designing an alarm that can continue to capture attention against an acoustic masker and when an alarm siren often sounds when no danger is present is an extremely important issue. In the latter case a cry-wolf effect can occur within which individuals ignore alarm signals when danger is present (Bliss, Washington & Fuller, 1994; Breznitz, 1983). For safety critical systems, it is important for an alarm to capture attention even when the probability of false alarm is high, since failing to respond to the alarm could result in possible injury or death within, for example, the hospital ward. It is hoped that my previous study (Hansson, 2017), current study, and forthcoming study can contribute some input or insights into effective alarm design.

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