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Evaluating Warning Sound Urgency With Reaction Times

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It is well-established that subjective judgments of perceived urgency of alarm sounds can be affected by acoustic parameters. In this study, the authors investigated an objective measurement, the reaction time (RT), to test the effectiveness of temporal parameters of sounds in the context of warning sounds. Three experiments were performed using a RT paradigm, with two different concurrent visuomotor tracking tasks simulating driving conditions. Experiments 1 and 2 show that RT decreases as interonset interval (IOI) decreases, where IOI is defined as the time elapsed from the onset of one sound pulse to the onset of the next. Experiment 3 shows that temporal irregularity between pulses can capture a listener's attention. These findings lead to concrete recommendations: IOI can be used to modulate warning sound urgency; and temporal irregularity can provoke an arousal effect in listeners. The authors also argue that the RT paradigm provides a useful tool for clarifying some of the factors involved in alarm processing.

Keywords: auditory warnings, psychophysics, attention

The use of sounds to present information is now relatively common in applications such as hospital equipment or aircraft navigation systems (Stanton & Edworthy, 1999). More recently, new in-car technologies have led to an increasing number of sound interfaces, ranging from information related to satellite navigation to warning signals used to alert drivers to potential danger. Among all potentially dangerous events that may be encountered while driving, some of them might now be avoided by using new technologies such as adaptive cruise control. In this scheme, the distance to other vehicles and the relative speed are calculated by in-car computers. When this distance is too small, for example, a warning signal informs the driver that he or she has to react as soon as possible. The question then becomes how to alert drivers to potential dangers and how to incite those drivers to act as quickly as possible. The main goal of the study presented in this article is to investigate the relevance of reaction time (RT) measurements to the evaluation of warning-sound urgency.

Until a few years ago, warning signals were designed without appropriate testing. R. D. Patterson first reported some of the problems typically associated with auditory displays from aviation or medical environments (Patterson, 1990; Patterson, Edworthy, Shailer, Lower, & Wheeler, 1986). One of the main problems that he highlighted was that warning signals can become a distraction during times of high workload, instead of just attracting listeners' attention and providing relevant information about a potential problem or sudden urgency.

On the basis of these observations, Patterson (1990) proposed a pragmatic methodology in four steps to design warning sounds in a high-workload environment. These four steps included determining the appropriate level of loudness, designing a small pulse of sound, incorporating the pulse into a longer burst of sounds, and forming a complete auditory warning signal using bursts of sounds followed by short periods of silence. His work was mainly focused on the first step, loudness level, which must take into account the background noise in which the sounds are to be heard. The three final steps were aimed at controlling the interpretation of the warning signal (design of pulse, burst, and warning signal). Patterson proposed that once the "structure" of the auditory warning was designed, the perceived urgency could be altered by adjusting the pitch, the intensity, and the speed of the burst.

To give precise recommendations on "urgency matching," that is, to associate the appropriate warning sound with the appropriate urgent situation, knowledge of the effect of sound parameters on perceived urgency is required. A first influential study (Edworthy, Loxley, & Dennis, 1991) showed that some pulse and burst parameters had clear and consistent effects on the perceived urgency of a warning sound. Edworthy et al. (1991) identified pulse parameters—such as fundamental frequency, harmonic series, amplitude envelope shape, and delayed harmonics, as well as temporal and melodic parameters such as speed, rhythm, pitch range, and melodic structure—and proposed that these parameters controlled the perceived urgency of the warning sounds. Specifically, subjective judgments indicated that the faster the rate, the higher the pitch, and that the more randomly irregular the frequencies of the harmonics, the greater the perceived urgency. Edworthy et al. also studied the effect of temporally unpredictable

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events on perceived urgency. They found that an irregular rhythm is perceived as slightly less urgent than is a regular one. However, it should be noted that the irregular rhythm was not random but was syncopated, that is, a regular rhythm with events occurring off the main beat period (e.g., Essens & Povel, 1985; Fraisse, 1982).

These results have been confirmed and extended in subsequent studies (e.g., Hellier & Edworthy, 1999; Hellier, Edworthy, & Dennis, 1993). Hellier et al. (1993) showed the existence of a power function relating acoustic parameters (rate, fundamental frequency, repetition number, and harmonic content) and perceived urgency. They also reported that some parameters contributed more to perceived urgency than did others, with rate being the most efficient parameter to communicate urgency.

Edworthy et al.'s (1991) alarm-design principles appear to be relatively robust (Guillaume, Pellieux, Chastres, & Drake, 2003; Hellier et al., 1993). On the basis of R. D. Patterson's four steps and these studies, urgency matching of alarm sounds thus seems possible: The warning sound perceived as most urgent can be associated with the most urgent situation. Finally, Walker (2002) showed that the psychophysical method used by Edworthy et al. (1991) and Hellier et al. (1993) for warning sounds could also be useful for developing effective data sonification, for which *sonification* is defined as a "particular type of auditory display, in which relationships in a data set are translated into, or represented by, sounds for the purpose of understanding or discovering patterns in the data set" (Walker, 2007, p. 579).

What Is Urgency?

The psychophysical approach adopted by Edworthy et al. (1991) has been further extended to investigate cognitive factors in perceived urgency. Guillaume et al. (2003) showed that although Edworthy et al.'s predictions were accurate for synthesized alarms, they were not entirely valid when applied to real alarms recorded from military aircrafts. Some real alarms did not follow the predicted pattern, because of a possible highly learned association between an alarm and its meaning by the operators. The authors concluded that the design of alarms should take into consideration the acquisition of what they called a "mental representation."

Thus, whereas the subjective "perceived urgency" approach has provided several useful experimental results, it is not clearly established what urgency is. According to common sense, urgency is what requires immediate action or attention. In realistic conditions, an urgent situation may occur under high workload. Auditory warnings might then signal potentially dangerous conditions or equipment malfunctions. As a result, the warning attracts attention, and the listener has to react immediately. Therefore, a warning signal is efficient when it increases the probability of an appropriate reaction under urgent conditions (Guillaume et al., 2003) with decreased RTs (Bliss, Gilson, & Deaton, 1995).

Consequently, in this study we ask the following questions: Do we react more rapidly to some sounds than to others? If we do, which improve our performance (in terms of a decrease in RT)? Answers to these questions should lead to a more appropriate understanding of at least one of the processes involved in urgent situations and to more useful recommendations of how to design powerful warning sounds.

Instead of using perceptual assessment, in which a listener has to make subjective judgments about the sounds that are played (e.g., which of the two sounds is the more urgent), we used an objective measurement, the RT. Since the work of Donders (1868/1969), chronometric analyses of mental processes have been performed with RT paradigms (for a complete review, see Luce, 1986). We concentrate in this study on a simple RT paradigm. Although it could be considered as an oversimplistic view of realistic conditions, it is a necessary first step before designing more complex experiments (such as multiple-choice RT) in which the appropriateness of the reaction could also be determined.

Such RT measurements in the context of warning sounds have already been investigated. In a first study, Burt, Bartolome, Burdette, and Comstock (1995) proposed that a faster RT would occur in response to the most urgent warning. However, RT did not differ significantly in response to the urgency levels tested (parameters tested were fundamental frequency and harmonic series, as was recommended by Edworthy et al., 1991). With these same parameters, Edworthy et al. (1991) did find differences in urgency judgments. Consequently, predictions about a possible link between higher urgency alarms and improvement in RT were not confirmed.

At the same time, Haas and Casali (1995) conducted a study investigating the effect of pulse format, pulse level, and interpulse interval on *subjective* perceived urgency and *objective* RT. They found that only pulse format (sequential pure tones, simultaneous pure tones, or frequency-modulated tones) and pulse level significantly influenced RT. However, each pulse had a duration of 350 ms, and they found a mean RT of approximately 450 ms. So interpulse interval could not have had an effect on RT by using these particular sounds, even though it might be an efficient parameter with other kinds of warning sounds.

Another purpose of Haas and Casali's (1995) study was to investigate the relationship between perceived urgency and RT. The authors found a correlation between the two measures: As perceived urgency increased, RT decreased. To explain this correlation, they assumed that higher-urgency alarms would appear more important to the listener, thus leading to a faster RT. This was, however, not the case, because at least one of the parameters tested (interpulse interval) lead to higher urgency but had no effect on RT. Moreover, the mechanisms by which perceived urgency judgments should produce a decrease in an objective measurement such as simple RT are unclear.

Finally, in industrial environments, listeners are often engaged in more than one task, which all require attention. Because real alarms are embedded within systems, it is important to study their effect in a realistic context and not in isolation. A dual-task paradigm is commonly used to determine the effect of the alarm and to evaluate attention and mental workload (Bliss et al., 1995; Burt et al., 1995; Haas & Casali, 1995; Sorkin, Kantowitz, & Kantowitz, 1988). For example, Burt et al. (1995) studied attentional engagement by manipulating two conditions of a tracking task, manual and automated. The authors showed, in line with classical findings on dual-task performance (Pashler & Johnston, 1998), that participants produced slower RTs during the manual tracking condition. More important, they also established that the Edworthy alarm-design principles were still reliable under high cognitive load.

The Present Experiments

In this study, we examined the influence of acoustic parameters on RT under high -workload conditions.

In Experiment 1, we investigated the influence of interonset interval (IOI) on RT to address the issue introduced by Haas and Casali (1995). IOI is the time elapsed from the onset of one pulse to the onset of the next. As was highlighted before, the authors did not find an effect of IOI on RT. However, we hypothesized that this lack of effect was due to the long pulse duration that they used (350 ms): The rhythm could not be heard before the listener reacted. In the present experiment, listeners were presented with a burst of short pulses (20 ms) that changed in IOI and were asked to press a response button as soon as they heard the sound. Listeners were also asked to perform simultaneously a primary tracking or monitoring task. The tracking condition of the primary task was designed to maintain a high level of attention at all times. Experiment 2 was partly suggested by results obtained in Experiment 1. The same stimuli as in Experiment 1 were used, but they were equalized in loudness to examine the effect of IOI on RT when any possible effect of loudness was removed. In Experiment 3, we continued the examination of the influence of temporal parameters on RT and introduced temporal irregularity. As was noted previously, temporally unpredictable events could be more attention-getting than predictable ones, but this assumption still needs to be demonstrated empirically. At the end of Experiments 1 and 3, participants rated the two different warnings (two IOIs and two temporal regularities) on an urgency rating scale.

The first issue addressed in this research concerns how IOI and temporal differences affect participants' RTs under high-workload conditions. The second issue concerns a comparison between subjective and objective measurements.

Experiment 1

Method

Participants

Thirteen participants (4 women; mean age ± standard deviation = 27.8 ± 2.4 years) were recruited from an existing database of volunteers. They were compensated for their participation. None of them reported having hearing problems. All were right-handed and reported normal or corrected-to-normal vision.

Stimuli

The template for the two different stimuli was an isochronous sequence of short pulses. Each pulse of the burst was a 1-kHz pure tone, 20 ms in duration, and included 5 ms linear onset and offset ramps. Stimuli varied along a single dimension, the IOI. The two IOIs tested were 100 ms and 300 ms. The total duration of each burst was 920 ms. It should be noted here that an IOI variation leads to a variation in the number of pulses in a burst. As the two stimuli had the same total duration, we could not study IOI and number of pulses as independent factors. We accepted this inevitable fact, and will henceforth only use the IOI terminology.

Apparatus

The sound samples were generated with a 44.1-kHz sampling rate under the control of a PC, using Matlab v.7 software. The sound samples were amplified by a Yamaha P2075 stereo amplifier and presented binaurally over a Sennheiser HD 250 linear II headphone set. Stimuli were presented at 76.5 dB SPL. The experimental sessions were run using a Max/MSP interface on an Apple computer. Participants responded by using the space bar of the computer keyboard placed on a table in front of them. The responses were recorded by Max/MSP, with a temporal precision for stimulus presentation and responses around 1 ms. The primary task was created using Jitter, the graphical part of Max/MSP. Performance on the tracking condition was recorded every 10 ms by calculating the distance between the target and the pointer. All data were collected in the computer memory for further off-line analysis. The experiments took place in a double-walled Industrial Acoustics Company (IAC) sound booth.

Procedure

The primary task consisted of two attentional conditions, called *tracking* and *monitoring*. During the tracking condition, participants were required to track a circular target manually, to keep it within a circular boundary that moved at a constant speed and in a random trajectory on the screen. Figure 1 shows the circular pointer (in white; orange in the real interface) and the target (concentric circles in gray). Participants had to perform the task with their nondominant hand. This made the tracking condition continuously demanding for each participant. It was necessary for the tracking condition to be challenging, so that the effort expended by the participants to perform it (and respond to the alarms) would approximate the effort experienced in many complex task situations (de Waard, 1996). Participants were instructed to optimize both response speed and accuracy of the tracking condition. During the monitoring condition, they were required to monitor visually the computer tracking of the circular target and to perform only the RT task. Although there was no measure of what participants really did during the monitoring condition, they were explicitly instructed to monitor the target visually.

Throughout the primary task, one exemplar of each of the two auditory warnings was presented in random order for each trial. Following a standard RT procedure, participants had to respond as soon as they detected the sound by pressing the space bar as fast as possible. They were asked to keep the finger of their dominant

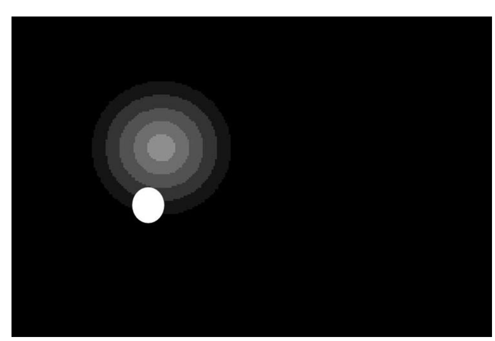

Figure 1. Screenshot of the tracking condition of the primary task used in Experiments 1, 2, and 3. The target is represented by different concentric circles in gray, and the pointer by a white circle (orange in the original experiment). Participants had to track with the mouse pointer (represented by the white circle) the target moving at a constant speed along a random trajectory on the screen.

hand in contact with the space bar between trials. The intertrial interval was randomly fixed between 3 and 8 s.

Prior to data collection, a short practice period of approximately 3 min was provided. The two conditions (tracking and monitoring) were presented three times each in counterbalanced order. Each participant thus participated in six experimental sessions, each session consisting of 50 stimuli. The stimuli of different IOI were randomly intermixed. The number of stimuli of different IOI was equal (25 each). RT scores were calculated for each IOI value in each block, attentional condition, and repetition. We thus obtained 300 RT scores from each participant.

During the first part of the experiment, no reference was made at any time to the concept of urgency or to alarms. After the first part of the experiment, participants were informed as to the goal of the study and were asked to perform the subjective task. They had to provide subjective urgency ratings by estimating the urgency of each warning on a continuous (rating) scale labeled *not urgent* and *very urgent* at the extremes. On each trial, the two warning sounds presented were recorded with the coded value of the cursor (0 at the far left for *not urgent* and 1 at the far right for *very urgent*). The entire experimental session lasted about 1 hr.

Statistical Approach

RT was defined as the time interval between the onset of a stimulus and the onset of a response. For each participant, RT distributions were recorded. Responses were first analyzed to detect errors and outlying points. Errors included anticipations (RTs less than 100 ms) and misses (failures to respond). Errors were discarded from the RT data and were replaced by the mean of the corresponding condition for each participant. Outliers in the responses were then considered. *Outliers* are defined as RTs generated by processes that are not the one being studied. These processes can be due to participants' inattention or to guesses based on participants' failure to reach a decision. Solutions to the problems of outliers rely on removing observations. Criteria for removing are, however, problematic because real data are inevitably rejected along with spurious data (e.g., Ratcliff, 1993; Ulrich & Miller, 1994). Despite this difficulty, outliers cannot be ignored, especially in paradigms in which frequent distraction is known to occur (Osborne & Overbay, 2004). There has been a lot of controversy over whether to remove outliers or not and over the methods used to remove outlying points (Ratcliff, 1979; Ulrich & Miller, 1994). We thus adopted two different approaches to analyze the RT data. First, we considered data without any form of outlier exclusion. Second, we adopted the most common procedure in RT analysis, that is, removing all observations greater than 2 standard deviations from the mean (Miller, 1991; see also Cardinal & Aitken, 2006). Missing data (i.e., excluded outliers) were replaced by the mean of the corresponding condition for each participant. We chose to compare RT analysis with and without outlier exclusion to have a better understanding of the underlying processes involved in the present experiments. The same approach in analyzing RT data was adopted for the three experiments presented in this article.

The RT data were averaged across the repetition factor, and a 2 (IOI) × 2 (attentional condition) × 3 (block) repeated-measures analysis of variance (ANOVA) was then performed, both with and without outlier removals. Participants were treated as a random-effect variable. The remaining variables were treated as fixed-effect variables. To account for violations of the sphericity assumption, p values were corrected using the Huynh-Feldt method. The ε value was computed to identify nonspherical data; $p < .05$ was considered to be statistically significant.

In a supplementary step, we analyzed a possible variable effect of the tracking condition over the three blocks. For each 10-ms period, the positions of the target and pointer were recorded, and the distance between them was computed. For each block, the mean and the standard deviation of all of these distances were calculated for each participant. We performed an ANOVA to investigate the effect of a possible improvement over blocks.

Results

RTs

No anticipations were found and only two misses were observed, one in each of the primary task conditions (tracking and monitoring); they were thus discarded before completing the following analyses.

Analysis on RT data including all observations. Distributions of these data resembled normal distributions (Kolmogorov–Smirnov test, $p > .05$). The repeated-measures ANOVA comparing RTs revealed a significant main effect of IOI, $F(1, 12) = 5.02$, $p < .05$, and a significant main effect of the attentional condition, $F(1, 12) = 99$, $p < .001$. None of the other effects were significant, that is, the main effect of the block and all the interactions ($p > .1$).

Mean RT decreased when IOI decreased. For both tracking and monitoring condition, the decrease was 10 ms on average (tracking condition: for IOI = 100 ms, $M = 396$ ms, $SD = 63$ ms; for IOI = 300 ms, $M = 406$ ms, $SD = 74$ ms. Monitoring condition: for IOI = 100 ms, $M = 297$ ms, $SD = 39$ ms; for IOI = 300 ms, $M = 307$ ms, $SD = 48$ ms). The data also showed that participants had significantly longer RTs during the tracking condition ($M = 401$ ms, $SD = 69$ ms) than during the monitoring condition ($M = 302$ ms, $SD = 43$ ms). This finding is in line with those in previous studies (Bliss et al., 1995; Burt et al., 1995).

Analysis on RT data with outlier exclusion. Overall, outliers accounted for 4% of the total number of trials (157 measurements). For the tracking condition, 38 were due to the fast-rate sound and 40 to the slow-rate sound; for the monitoring condition, 33 were due to the fast-rate sound and 46 to the slow-rate sound.

We thus analyzed RT data after removing these outliers. Distributions of the RT data resembled normal distributions (Kolmogorov–Smirnov test, $p > .05$). The repeated-measures ANOVA comparing RTs revealed a significant main effect of IOI, $F(1, 12) = 14.74$, $p < .005$, a significant main effect of the attentional condition, $F(1, 12) = 107.90$, $p < .001$, and a significant main effect of the interaction between IOI and attentional condition, $F(1, 12) = 5.8$, $p < .05$. None of the other effects were significant ($p > .1$).

As in the previous analysis, the data showed that mean RT decreased when IOI decreased. However, in the current analysis (i.e., with outlier exclusion), the decrease was larger in the tracking condition (15 ms) than in the monitoring condition (6 ms). This result is consistent with the larger number of outliers observed in response to the slow-rate sound in comparison with the fast-rate sound during the tracking condition. These observations were confirmed by a significant interaction between IOI and attentional condition (tracking condition: for IOI = 100 ms, $M = 376$ ms, $SD = 53$ ms; for IOI = 300 ms, $M = 391$ ms, $SD = 58$ ms. Monitoring condition: for IOI = 100 ms, $M = 292$ ms, $SD = 36$ ms; for IOI = 300 ms, $M = 298$ ms, $SD = 38$ ms). Figure 2 depicts mean RT as a function of IOI in the tracking and monitoring conditions. Each bar represents the mean of 975 RT trials (75 per participant).

Performance on Tracking Condition

The data showed a significant effect of Block on the mean distance between target and pointer, $F(2, 24) = 9.06$, $\varepsilon = .9$, $p < .002$, and a significant effect of Block on the standard deviation, $F(2, 24) = 6.02$, $\varepsilon = 1$, $p < .01$. The mean distance and the standard deviation decreased throughout the blocks. These effects could be seen as learning effects: Performance on the tracking condition became more accurate and increasingly stable over the blocks.

Urgency Judgment

Participants rated signals with an IOI of 300 ms ($M = 0.2$, $SD = 0.1$) as sounding less urgent than the one with an IOI of 100 ms ($M = 0.7$, $SD = 0.2$), $t(26) = -8.6$, $p < .001$. This result is consistent with previous findings (Edworthy et al., 1991; Hellier et al., 1993).

Discussion

One of the issues of this study concerned the comparison between subjective and objective measurements. Haas and Casali (1995) examined the relationship between perceived urgency and RT to warning signals. Their results suggested that there was a correlation between the two measurements: As perceived urgency increased, RT decreased. Their design prevented them from testing the effects of IOI, however. The outcome of Experiment 1 thus extends these previous results and shows that short IOIs lead to faster RTs and higher urgency judgments. Such a correlation does not imply that perceived urgency and RT share common perceptual and cognitive mechanisms, however, and the present experiment does specify the potentially different mechanisms underlying subjective and objective urgency.

The second aim of this experiment concerned how IOI would affect participants' RTs under high-workload conditions. The outcome of Experiment 1 first showed that there was a straightforward relation between attention and RT: Specifically, RTs in the tracking condition were longer than RTs in the monitoring condition. This result provides support for previous findings (Bliss et al., 1995; Burt et al., 1995; for a more theoretical point of view, see Pashler & Johnston, 1998). As has already been mentioned, it strongly suggests the existence of capacity limits in perceptual analysis. It means that a portion of the capacity is allocated for tracking performance: The more difficult the primary task, the greater the mean RT.

More interestingly, a significant interaction between task and IOI was observed, and this interaction appeared significant only in the analysis with outlier exclusion. This is coherent with the distribution of outliers as a function of IOI: During the monitoring task, more outliers were observed in response to the slow sound, whereas outliers were equally distributed as a function of IOI during the tracking condition. Two points can be highlighted here. First, if we assume that outliers were generated by participants' inattention, we can conclude that the slow-rate sound was less efficient in capturing attention because it elicited more outliers than did the fast-rate sound, especially in a nonattentional task. Second, we observed that IOI had a greater influence on RT when participants were under high attentional demand (simulating a driving situation, for instance). This finding is crucial from an applied point of view. One could argue that the IOI effect observed

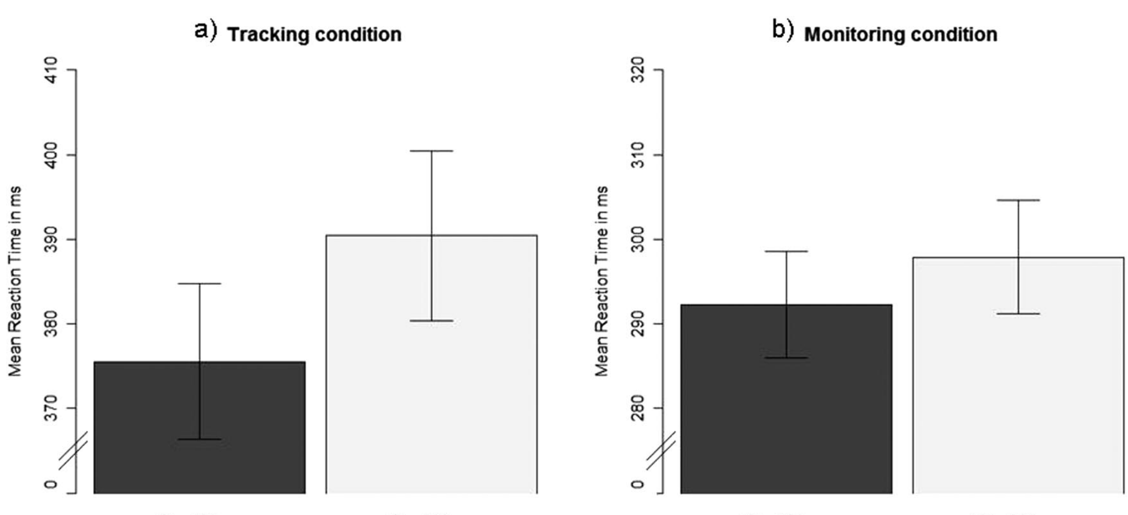

Figure 2. Mean reaction time as a function of interonset interval (IOI) in (A) the tracking condition and (B) the monitoring condition (Experiment 1, analysis with outlier exclusion). The vertical lines represent the standard error of the mean.

in this study is too small for practical purposes. However, the interaction observed suggests that under a real urgent situation with an even greater workload, IOI would have a greater effect, because of the interaction with other cognitive and motor processes that would be in play.

Overall, results obtained in Experiment 1 highlighted a main effect of IOI on RT. The IOI effect apparently reflected a general process that occurred under different attentional conditions. Our stimuli were not equalized in loudness, however, which could explain part of this result. Stimuli were designed to vary in terms of IOI and were presented at a fixed level of 76.5 dB SPL, to simulate realistic warnings. On the basis of recent studies concerning the loudness of modulated sounds, the two different time-varying sounds presented during the experiment at the same maximum level might have different loudnesses (for reviews, data, and models on the loudness of amplitude-modulated sinusoidal carriers, see Moore, Vickers, Baer, & Launer, 1999; Glasberg & Moore, 2002). Figure 3 shows main results of the predictions of Glasberg and Moore's (2002) time-varying model. The short-term loudness for the fast-rate sound (IOI = 100 ms) was slightly higher in response to the second pulse (69.4 phons) than in response to the first (68.3 phons): A form of temporal integration occurred. This effect was negligible for the slow rate (IOI = 300 ms), for which the loudness was 68.3 phons for the first and second pulses. The second pulse of the slow-rate sound and the fourth pulse of the fast-rate sound both occurred at $t = 320$ ms. As can be seen in Figure 3, short-term loudness at $t = 320$ ms for the fast-rate sound was higher (69.5 phons) than that for the slow-rate sound (68.3 phons). The same values were observed at $t = 620$ ms and $t = 920$ ms. There was thus a small loudness difference between the two sounds.

Previous experiments (Arieh & Marks, 2003; Chocholle, 1940; Kohfeld, Santee, & Wallace, 1981; Wagner, Florentine, Buus, & McCormack, 2004) evaluated the relation between loudness and RT. Their results showed that RT was closely related to loudness: Simple RTs decreased monotonically when sound intensity increased, and equally loud stimuli produced equal RTs regardless of stimulus frequency.

Even though the loudness difference between sounds was very small, one cannot rule out that the effects of IOI in Experiment 1 were confounded by a loudness effect. Experiment 2 was performed to investigate this possibility.

Experiment 2

Method

Participants

Thirteen new participants (5 women; mean age ± standard deviation = 26.5 ± 1.7 years) were recruited from an existing database of volunteers for this experiment. They were compensated for their participation. None of the participants reported having hearing problems. All of them were right-handed and reported normal or corrected-to-normal vision.

Stimuli

Loudness equalization was performed on the two stimuli described in Experiment 1. A group of 14 other listeners participated in this preliminary experiment. Loudness matches between the fast-rate and slow-rate sounds were obtained with an adjustment procedure (Buus, Greenbaum, & Scharf, 1982). The listener was

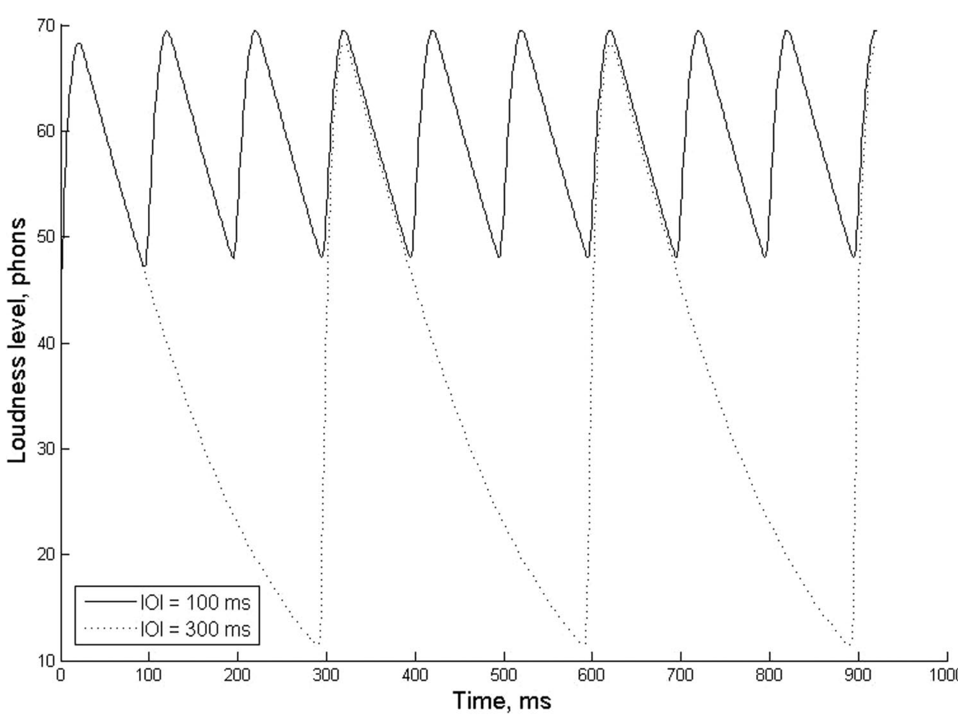

Figure 3. Time-varying model (Glasberg & Moore, 2002) showing short-term loudness as a function of time in response to the two stimuli.

asked to adjust the comparison stimulus until it seemed equal in loudness to the standard stimulus. The fast-rate sequence was used as the comparison and the slow-rate sequence as the standard. The level of the slow-rate stimulus was fixed at 76.5 dB, as in Experiment 1. The mean level difference at which the slow-rate and fast-rate sequences were judged to be equal in loudness was 5.4 dB SPL.

Apparatus, Procedure, and Statistical Approach

These were the same as in Experiment 1, except that we did not include the urgency judgment. The slow-rate and fast-rate stimuli were presented at 76.5 dB SPL and 71.1 dB SPL, respectively.

Results

RTs

No anticipations were found, and only three misses were observed during the monitoring condition. They were discarded before conducting the following analyses.

Analysis on RT data including all observations. Distributions of these data resembled normal distributions (Kolmogorov–Smirnov test, $p > .05$). The repeated-measures ANOVA comparing RT revealed a significant main effect of IOI, $F(1, 12) = 8.99$, $p < .05$, and a significant main effect of the attentional condition, $F(1, 12) = 41.84$, $p < .001$ (tracking condition: for IOI = 100 ms, $M = 333$ ms, $SD = 42$ ms; for IOI = 300 ms, $M = 342$ ms, $SD = 47$ ms. Monitoring condition: for IOI = 100 ms, $M = 270$ ms, $SD = 34$ ms; for IOI = 300 ms, $M = 276$ ms, $SD = 38$ ms). None of the other effects were significant ($p > .3$). These results are similar to those observed in Experiment 1.

Analysis on RT data with outlier exclusion. Outliers accounted for 4.5% of the error-free trials (174 measurements). For the tracking condition, 47 were due to the fast-rate sound and 42 to the slow-rate sound; for the monitoring condition, 37 were due to the fast-rate sound and 48 to the slow-rate sound.

We thus analyzed RT data after removing these outliers. Distributions of the RT data resembled normal distributions (Kolmogorov–Smirnov test, $p > .05$). The repeated-measures ANOVA comparing RTs revealed a significant main effect of IOI, $F(1, 12) = 8.38$, $p < .05$, a significant main effect of the attentional condition, $F(1, 12) = 43.82$, $p < .001$, and a significant main effect of the interaction between IOI and attentional condition, $F(1, 12) = 5.04$, $p < .05$ (tracking condition: for IOI = 100ms, $M = 320$ ms, $SD = 61$ ms; for IOI = 300 ms, $M = 331$ ms, $SD = 70$ ms. Monitoring condition: for IOI = 100 ms, $M = 267$ ms, $SD = 56$ ms; for IOI = 300 ms, $M = 269$ ms, $SD = 57$ ms). None of the other effects were significant ($p > .5$). These results are similar to those observed in Experiment 1. Figure 4 depicts mean RT as a function of IOI in the tracking and monitoring conditions. Each bar represents the mean of 975 RT trials (75 per participant).

Performance on Tracking Condition

As was explained in Experiment 1, we performed an ANOVA to investigate the effect of learning over blocks. The data showed a significant effect of block on the mean distance, $F(2, 24) = 4.03$, $p < .05$, and a nonsignificant effect on the standard deviation between target and pointer, $F(2, 24) = 1.49$, $p = .24$. Participants' performance was more accurate across blocks.

Comparison of Experiments 1 and 2

To compare results of Experiment 1 and 2, we performed an additional mixed ANOVA on data with outlier exclusion, with *experiment* as a between-subjects factor and IOI, attentional condition, and block as within-subject factors. As was expected from the separate analysis of Experiments 1 and 2, the mixed ANOVA

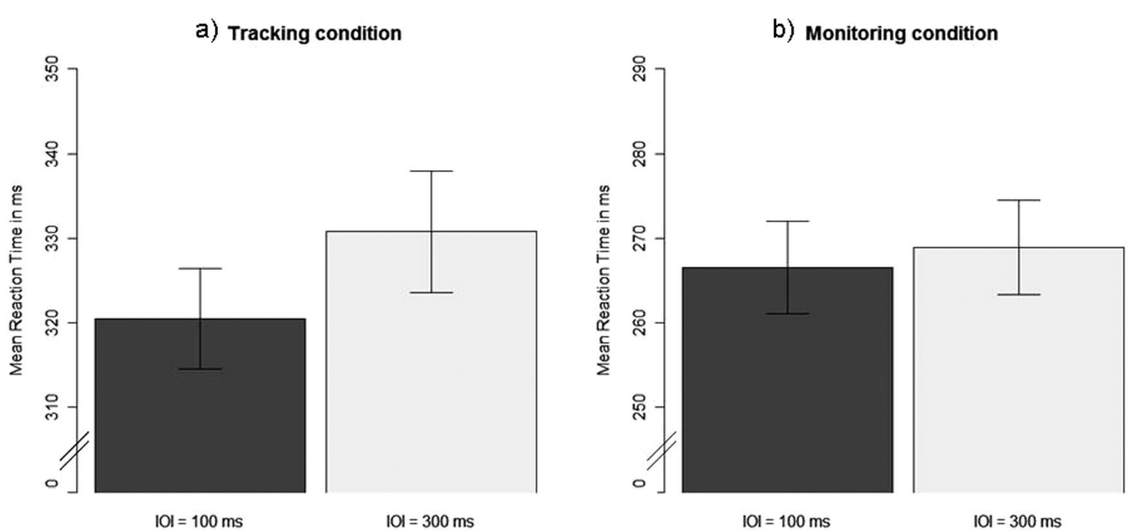

Figure 4. Mean reaction time as a function of interonset interval (IOI) in (A) the tracking condition and (B) the monitoring condition (Experiment 2, stimuli equalized in loudness, analysis with outlier exclusion). The vertical lines represent the standard error of the mean.

revealed significant main effects of IOI, $F(1, 24) = 23.09$, $p < .001$, and attentional condition, $F(1, 24) = 143.52$, $p < .001$, and a significant interaction between them, $F(1, 24) = 10.84$, $p < .005$. The ANOVA also revealed a significant main effect of *experiment*, $F(1, 24) = 7.90$, $p < .01$, and a significant interaction between task and *experiment*, $F(1, 24) = 6.07$, $p < .05$.

Discussion

The major purpose of this experiment was to examine whether we could still observe RT differences in response to stimuli with different IOIs that were equalized in loudness. As was noticed before, RT has been shown to vary with loudness (e.g., Chocholle, 1940; Wagner et al., 2004). If loudness was the only factor responsible for the RT effect observed in Experiment 1, no RT differences should be observed in Experiment 2, in which stimuli were equalized in loudness.

The most significant feature of Experiment 2 is that RT patterns similar to those of Experiment 1 were observed: RTs were smaller for the fast-rate sound than for the slow-rate sound. This was confirmed by a mixed ANOVA, which exhibited the same significant effects as the two separate analyses of Experiments 1 and 2 (the two additional effects related to the *experiment* factor could be easily explained by individual differences, which are commonly observed in RT paradigms; see Luce, 1986). Overall, this experiment provides evidence that RT were sensitive to an IOI effect with or without small differences in loudness.

This finding indicates that RT is not simply a function of the amount of stimulus energy, obtained by continuous integration over time. An alternative to continuous integration is the "multiple-looks" model of temporal integration in the auditory system (Viemeister & Wakefield, 1991). This model assumes that the nervous system combines multiple "looks" or "samples" of the stimulus to achieve its detection. When a listener is trying to detect a sound, short-term integration is done at a high rate (a few milliseconds): The auditory system takes multiple looks at the ongoing signal. A look constitutes the minimum integration time of the auditory system. Information from each individual look is then stored in memory and combined later to compute a decision statistic: This is the long-term integration of the process.

The multiple-looks model seems to be able explain our results, at least qualitatively. The number of sampling opportunities is higher for the fast-rate sound than for the slow-rate one. As the number of samples increases, the probability of detection increases, and accordingly, listeners reacted faster to the fast-rate stimulus.

The data of Experiment 2 may also be explained in terms of the number of stimulus pulses. With this point of view, it might be possible that listeners responded when a sufficient number of pulses occurred within a particular time window. However, because we had to control for the stimulus durations, we were not able to distinguish between the two possibilities of IOI and number of pulses.

In conclusion, the first temporal parameter of IOI studied in Experiments 1 and 2 has a clear and consistent effect on RT, which extends previous results of the urgency literature (Edworthy et al., 1991; Hellier et al., 1993).

Experiment 3

Unpredictable event sequences, such as those with rhythmic irregularity, have been suggested to be more attention-getting than are predictable regular sequences. However, no experimental data are available to support this hypothesis. In Experiment 3, we repeated the same paradigm as before but with sounds varying along a temporal irregularity dimension.

Method

Participants

Thirteen new participants (6 women; mean age ± standard deviation = 27 ± 2.1 year) were recruited from an existing database of volunteers for this experiment. They were compensated for their participation. None of them reported having hearing problems. All participants were right-handed and reported normal or corrected-to-normal vision.

Stimuli

The template for the two different stimuli was a sequence of five short pulses, with a total duration of 540 ms. Each pulse of the burst was a 1-kHz pure tone, 20 ms in duration, and included 5-ms linear onset and offset ramps. Stimuli varied along the temporal regularity dimension. Two temporal patterns were chosen, a regular and an irregular one. The regular one had an IOI of 130 ms. The irregular one was derived from this basic sequence, by displacing the second, third, and fourth pulses by 40 ms, which resulted in a lengthening or shortening of the intervals in the sequence. The IOI sequence was {90; 210; 50; 170} ms.

Apparatus, Procedure, and Statistical Approach

These were the same as in Experiment 1, replacing the IOI factor with the temporal irregularity factor.

Results

RTs

No anticipations were found, and only eight misses were observed, three in the monitoring condition and five in the tracking condition. They were thus discarded before conducting the following analyses.

Analysis on RT data, including all observations. Distributions of these data resembled normal distributions (Kolmogorov–Smirnov test, $p > .05$). The repeated-measures ANOVA comparing RTs revealed significant main effects of temporal differences, $F(1, 12) = 8.98$, $p < .05$, and attentional condition, $F(1, 12) = 45.79$, $p < .001$ (tracking condition: for the regular sound, $M = 411$ ms, $SD = 147$ ms; for the irregular sound, $M = 401$ ms, $SD = 132$ ms. Monitoring condition: for the regular sound, $M = 296$ ms, $SD = 87$ ms; for the irregular sound, $M = 291$ ms, $SD = 81$ ms). It should be noted here that the standard deviations were larger than those in the two previous experiments and, more generally, larger than what would be expected in a RT paradigm (Luce, 1986). None of the other effects were significant ($p > .4$).

Figure 5 depicts mean RT as a function of temporal difference in the tracking (panel A) and monitoring (panel B) conditions. Each bar represents the mean of 975 RT trials (75 per participant).

Analysis on RT data with outlier exclusion. Outliers accounted for 5% of the error-free trials (198 measurements). For the tracking condition, 64 were due to the regular sound and 37 to the irregular sound; for the monitoring condition, 54 were due to the regular sound and 43 to the irregular sound.

We analyzed the data after removing these outliers. Distributions of these data resembled normal distributions (Kolmogorov–Smirnov test, $p > .05$). The repeated-measures ANOVA comparing RTs revealed a significant main effect of attentional condition, $F(1, 12) = 51.23$, $p < .001$ (tracking condition: for the regular sound, $M = 386$ ms, $SD = 78$ ms; for the irregular sound, $M = 386$ ms, $SD = 77$ ms. Monitoring condition: for the regular sound, $M = 287$ ms, $SD = 49$ ms; for the irregular sound, $M = 284$ ms, $SD = 47$ ms). None of the other factors (including the temporal differences factor) or interactions were significant ($p > .1$).

Figure 5 depicts mean RT as a function of temporal differences in the tracking (panel C) and monitoring (panel D) conditions. Each bar represents the mean of 975 RT trials (75 per participant).

Performance on Tracking Condition

The data showed a significant effect of block on the mean distance between target and pointer, $F(2, 24) = 8.75$, $\varepsilon = .8$, $p < .01$, and on the standard deviation, $F(2, 24) = 5.29$, $\varepsilon = .9$, $p < .05$. There was still a small effect of learning.

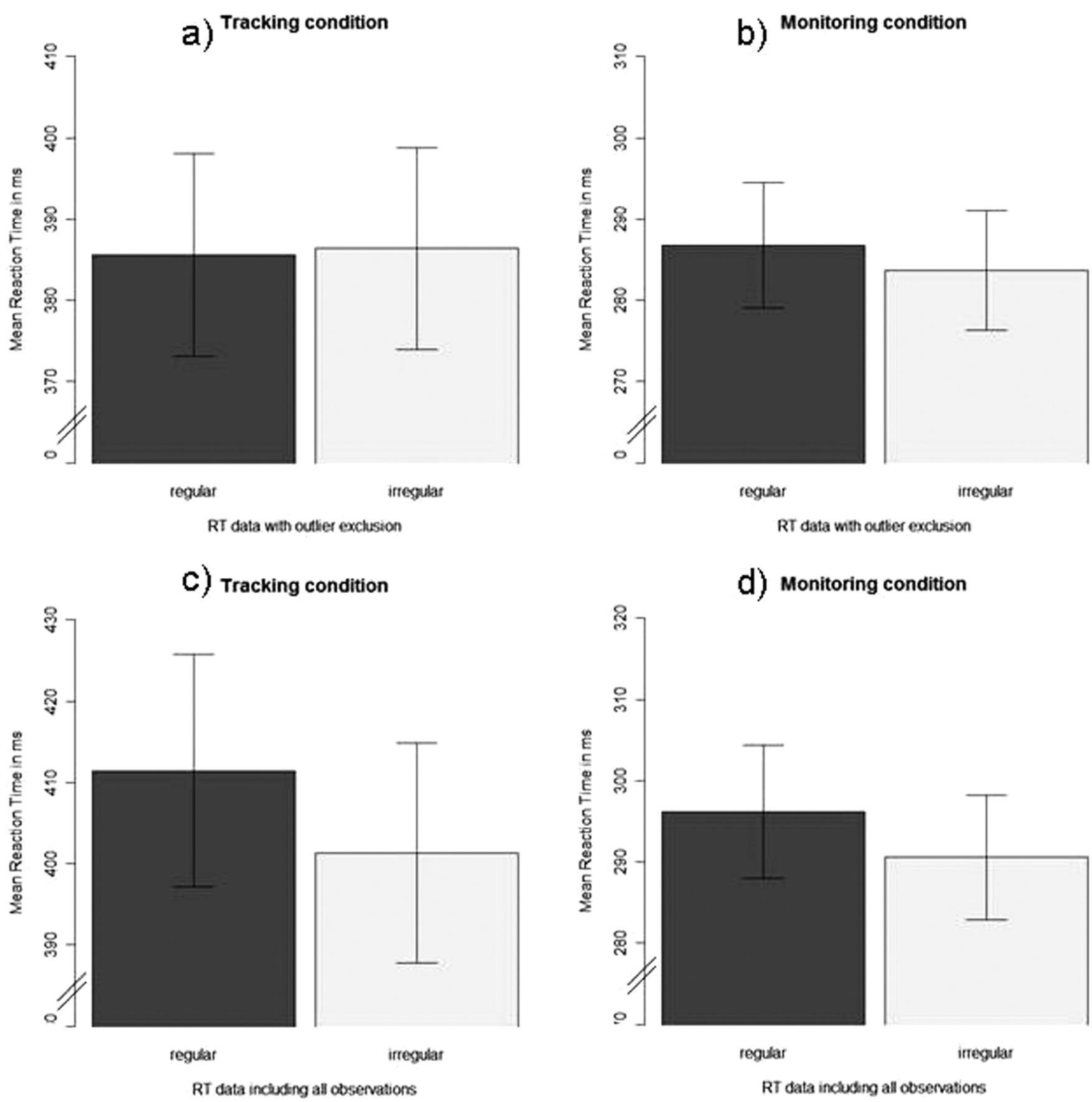

Figure 5. Mean reaction time (RT) as a function of temporal differences (Experiment 3) for the analysis with outlier exclusion (panel A: tracking condition; panel B: monitoring condition) and the analysis including all observations (panel C: tracking condition; panel D: monitoring condition).The vertical lines represent the standard error of the mean.

Urgency Judgment

Participants rated regular sounds ($M = .49$, $SD = .2$) as sounding as urgent as irregular ones ($M = .47$, $SD = .2$), $t(24) = 0.17$, $p = .8$.

Discussion

The first outcome of the third experiment was the characterization of RT for temporally irregular stimuli. We asked whether a significant increase or decrease in RT would be observed when the temporal irregularity was manipulated.

The analysis of data with outlier exclusion led to the conclusion that temporal differences did not elicit any significant improvement on RT. Thus, temporal differences could not be used to modulate urgency of warning sounds. However, the analysis of data, including all observations, highlights a significant effect of the temporal differences factor. Because outliers (included in this analysis) are the result, in the most common case, of participants' inattention, this finding suggests that temporal irregularity captured listeners' attention and tended to trigger responses more rapidly. In other words, outliers occurred less often in response to irregular stimuli than to regular stimuli. Thus, outliers showed a kind of "arousal effect" of temporal irregularity: Participants' attention was "captured" by temporally perturbed events.

The Dynamic Attending Theory (Jones, 1976; Jones & Boltz, 1989) proposes a theoretical framework of how listeners respond to and use tempo and time hierarchies. Jones (2004) further suggested that the degree of rhythmic regularity of an event time structure affects how effectively one attends to it. This theory is based on the principle of synchrony. The author assumed that rhythm is perceived in relation to the activity of a small system of internal oscillations. Attending is thus described as the synchronization of these internal attending periodicities with the external rhythm of an auditory sequence. Jones considered two aspects of attending: anticipatory attending and reactive attending. First, the listener can anticipate when the next time interval will begin: There is a shift of attending to coincide with expected sound onsets. Such anticipations are called *temporal expectancies*. The second aspect involves expectancy violations. Any deviation observed by the listener from an expected timing is an *expectancy violation*. Reactive attending involves rapid attentional shifts associated with unexpected sound onsets.

Our results are consistent with Jones' suggestion that a temporally irregular event may be more salient than are temporally expected ones in a very regular context. For a listener attending to a rhythmic sound pattern, a temporally unexpected sound is considered as an expectancy violation. This "surprise" contributes to a tuning of a listener's attention.

Another finding of this study that requires comment in light of the literature on perceived urgency is the finding of an absence of significant effect of temporal regularity on perceived urgency. Edworthy et al. (1991) suggested that there may be a weak relationship between a syncopated rhythm and perceived urgency. With a nonmetric rhythm, we did not observe any difference on perceived urgency between the two sounds.

General Discussion

Until now, the most dominant approach in urgency studies (e.g., Edworthy et al., 1991; Hellier et al., 1993) has been to measure the subjective perceived urgency of alarm sounds in relation to their acoustical properties, such as rate, pitch, or timbre. Showing that the ranking of alarms on an urgency scale could be modified by "high-level" parameters, Guillaume et al. (2003) extended these studies by adding an "activation of a mental representation" stage. Perceived urgency judgments could be modified by cognitive factors such as learning effects, cultural influences, participants' strategies, and the set of stimuli under study. We proposed here to consider the urgency issue in a more objective way by designing a new urgency paradigm based on RT measurement. We argue that, although a correlation could be observed between RT and perceived urgency, it does not imply that the processes underlying changes in perceived urgency are necessarily the same as those underlying changes in RT.

Several models have been proposed to account for auditory processing (McAdams & Bigand, 1994). This study first focused on "low-level" stages of the urgency process (Experiments 1 and 2). The observed behavioral performance apparently reflects processes occurring before the computation of perceptual properties or the "mental representation" stage. Experiment 3 complements this conclusion, showing that attentional processes might be affected by perceived regularities in the stimulus structure. The current findings thus highlight both stimulus-driven and expectancy-based representations of alarm sounds.

Results of Experiment 1 and 2 show a clear and consistent effect of IOI on RT. It has been proposed that the two necessary components in the RT response are signal detection and response initiation (e.g., Green & Luce, 1971). This means that the overall RT measures contain a motor component that complicates the estimation of the relation between the stimulus parameter under study— IOI—and the detection ("sensory") component (Kohfeld, 1971). Because the motor-execution stage has been proven to be relatively invariant across changes in perceptual and cognitive task requirements (Miller & Low, 2001), we assume that RT differences are attributable to differences in the durations of sensory or cognitive processes rather than to differences in motor time.

Experiment 1 stimuli varied (weakly) along the loudness dimension. Because RTs have already been used as an indirect measure of loudness for tones or noises (e.g., Chocholle, 1940; Wagner et al., 2004), we first hypothesized that this IOI effect observed in Experiment 1 would partially or perhaps entirely be due to the loudness difference between the two sounds.

In Experiment 2, we asked whether the IOI effect would be observed when stimuli were equalized in loudness. Results still support a clear effect of IOI on RT; stimuli with lower IOI provoke a faster RT. The multiple-look model (Viemeister & Wakefield, 1991) seems able to explain at least qualitatively our data. Instead of continuous integration, samples at the output of initial processing stages in the auditory system could be used and selected to result in faster RTs.

In Experiment 3, when manipulating temporal regularity, we found no RT differences. However, a careful study of outlier data shows that outliers were much more common in response to the regular sounds than to the irregular sounds. This result could be interpreted as a capture of a listener's attention by temporal irregularity. Indeed, rhythmic expectancies generated by hearing regular sequences within the same session might lead to expectancy violations that can capture attending (Jones, 2004).

Another noteworthy result observed in the three experiments was the comparison of RT between the tracking condition and the monitoring condition. Mean RTs were slower under high attentional demands (tracking condition) than under a simple monitoring condition. This result is consistent with the literature on dual-task paradigms (Pashler & Johnston, 1998). When a task is performed as a switch trial, there is a sizable decrement in performance (increased RT). This decrement is called the *shift cost* (for a review, see Hsieh, 2002). Interestingly, the size of the IOI effect was larger in the tracking condition than in the monitoring condition. This plainly demonstrates the potential benefit of using a RT paradigm under attentional conditions simulating realistic conditions, such as a driving situation, for instance. It is likely that RT differences elicited by different IOIs in a real, urgent situation could be even larger than what we observed under laboratory conditions.

We should finally point out here that a simple RT task may simulate only the first part of a more global warning process. Simple RT tasks require participants to respond to all stimuli with a single type of action. In a real situation, even if a fast reaction is required, the type of reaction to perform has to be evaluated. Our use of a simple RT model of a real-world warning situation could also explain why the differences between warning signals were relatively small (around 10 ms). A more complex simulation would likely lead to greater benefits of one warning sound over another, because of the involvement of additional perceptual and cognitive processes. Future designs of urgency experiments should use a multiple-choice RT task, reflecting more closely the final application (e.g., “Should I brake or accelerate?”).

Whereas the warning sounds presented here have to be studied under more complex simulations of the real application (such as in a car simulator), this simple RT study is still a crucial step in understanding more precisely the warning process. Efficient alarms are those that are, first and foremost, detected and processed more rapidly. Warnings can be designed on an IOI scale, with the faster IOI associated with the most urgent warning. Moreover, temporal irregularity can be used as a “wake-up” warning in potential situations of driver inattention.

Conclusion

We carried out three experiments to better understand and extend existing recommendations on auditory warning design. We have demonstrated the importance of temporal factors (IOI and temporal differences) by the use of an objective measurement (RT). We have shown that efficient alarms should be designed according to an IOI scale: The shorter the IOI, the more urgent, and the faster the response of the operator. Moreover, we have broadened the possible applications of temporal factors in warning-sound design by adding a temporal irregularity parameter that has an “arousal” effect on participants. Interestingly, also, we have shown that the size of the IOI effect was larger under high attentional demands, highlighting the benefit of studying alarms under conditions simulating real situations (such as driving).

This RT paradigm not only leads to concrete recommendations concerning the design of alarms but also provides a better understanding of the processes involved when reacting to those alarms. A decrease in IOI leads to a decrease in RT, probably because of the form of the temporal integration process in the auditory system. In addition to this “low-level” process, the arousal effect of temporal irregularity could be an illustration of a more “high-level” mechanism that determines how listeners respond to and use time hierarchies.

References

Arieh, Y., & Marks, L. E. (2003). Recalibrating the auditory system: A speed-accuracy analysis of intensity perception. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 523–536.

Bliss, J. P., Gilson, R. D., & Deaton, J. E. (1995). Human probability matching behaviour in response to alarms of varying reliability. *Ergonomics, 38,* 2300–2312.

Burt, J. L., Bartolome, D. S., Burdette, D. W., & Comstock, J. R., Jr. (1995). A psychophysiological evaluation of the perceived urgency of auditory warning signals. *Ergonomics, 38,* 2327–2340.

Buus, S., Greenbaum, H., & Scharf, B. (1982). Measurements of equal loudness and reaction times. *Journal of the Acoustical Society of America, 72*(Suppl. 1), 594.

Cardinal, R. D., & Aitken, M. R. F. (2006). *ANOVA for the behavioural sciences researcher.* New Jersey: Erlbaum.

Chocholle, R. (1940). Variations des temps de réaction auditifs en fonction de l’intensité à diverses fréquences [Variation in auditory reaction time as a function of intensity at various frequencies″]. *L’Année Psychologique, 41,* 65–124.

de Waard, D. (1996). *The measurement of drivers’ mental workload.* Unpublished doctoral dissertation, University of Groningen, Traffic Research Centre, Haren, The Netherlands.

Donders, F. C. (1969). On the speed of mental processes. *Acta Psychologica, 30,* 412–431. (Translation of Die Schnelligkeit psychischer Processe, first published in 1868.)

Edworthy, J., Loxley, S., & Dennis, I. (1991). Improving auditory warning design: Relationship between warning sound parameters and perceived urgency. *Human Factors, 33,* 205–231.

Essens, P. J., & Povel, D. J. (1985). Metrical and nonmetrical representations of temporal patterns. *Perception and Psychophysics, 37,* 1–7.

Fraisse, P. (1982). Rhythm and tempo. In D. Deutsch (Ed.), *The psychology of music* (pp. 149–180). New York: Academic Press.

Glasberg, B. R., & Moore, B. J. C. (2002). A model of loudness applicable to time-varying sounds. *Journal of the Audio Engineering Society, 50,* 331–342.

Green, D. M., & Luce, R. D. (1971). Detection of auditory signals presented at random times: III. *Perception and Psychophysics, 9,* 257–268.

Guillaume, A., Pellieux, L., Chastres, V., & Drake, C. (2003). Judging the urgency of nonvocal auditory warning signals: Perceptual and cognitive processes. *Journal of Experimental Psychology: Applied, 9,* 196–212.

Haas, E. C., & Casali, J. G. (1995). Perceived urgency of and response time to multi-tone and frequency-modulated warning signals in broadband noise. *Ergonomics, 38,* 2313–2326.

Hellier, E. J., & Edworthy, J. (1999). On using psychophysical techniques to achieve urgency mapping in auditory warnings. *Applied Ergonomics, 30,* 167–170.

Hellier, E. J., Edworthy, J., & Dennis, I. (1993). Improving auditory warning design: Quantifying and predicting the effects of different warning parameters on perceived urgency. *Human Factors, 35,* 693–706.

Hsieh, S. (2002). Task shifting in dual-task settings. *Perception and Motor Skills, 94,* 407–414.

Jones, M. R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. *Psychological Review, 83,* 323–355.

Jones, M. R. (2004). Attention and timing. In J. Neuhoff (Ed.), *Ecological psychoacoustics* (pp. 49–88). San Diego, CA: Elsevier Academic Press.

Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological Review, 96,* 459–491.

Kohfeld, D. L. (1971). Simple reaction time as a function of stimulus intensity in decibels of light and sound. *Journal of Experimental Psychology, 88,* 251–257.

Kohfeld, D. L., Santee, J. L., & Wallace, N. D. (1981). Loudness and reaction time: I. *Perception and Psychophysics, 29,* 535–549.

Luce, R. D. (1986). *Response times: Their role in inferring elementary mental organization.* New York: Oxford University Press.

McAdams, S., & Bigand, E. (1994). *Penser les sons. Psychologie cognitive de l'audition* [Thinking sounds]. Paris: Presses Universitaires de France.

Miller, J. O. (1991). Reaction time analysis with outlier exclusion: Bias varies with sample size. *Quarterly Journal of Experimental Psychology, Section A: Human Experimental Psychology, 43,* 907–912.

Miller, J. O., & Low, K. (2001). Motor processes in simple, go/no-go, and choice reaction time tasks: A psychophysiological analysis. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 266–289.

Moore, B. J. C., Vickers, D. A., Baer, T., & Launer, S. (1999). Factors affecting the loudness of modulated sounds. *Journal of the Acoustical Society of America, 105,* 2757–2772.

Osborne, J. W., & Overbay, A. (2004). The power of outliers (and why researchers should always check for them). *Practical Assessment, Research, and Evaluation, 9,* 1–10.

Pashler, H. E., & Johnston, J. C. (1988). Attentional limitations in dual-task performance. In H. E. Pashler (Ed.), *Attention* (pp. 155–189). Hove, UK: Psychology Press.

Patterson, R. D. (1990). Auditory warning sounds in the work environment. *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences, 327,* 485–492.

Patterson, R. D., Edworthy, J., Shailer, M., Lower, M., & Wheeler, P. (1986). *Alarm sounds for medical equipment in intensive care areas and operating theatres.* (Tech. Rep. No. AC589). Southampton, UK: University of Southampton, Institute of Sound and Vibration Research.

Ratcliff, R. (1979). Group reaction time distributions and an analysis of distribution statistics. *Psychological Bulletin, 86,* 446–461.

Ratcliff, R. (1993). Methods for dealing with reaction time outliers. *Psychological Bulletin, 114,* 510–532.

Sorkin, R. D., Kantowitz, B. H., & Kantowitz, S. C. (1988). Likelihood alarm displays. *Human Factors, 30,* 445–459.

Stanton, N. A., & Edworthy, J. (1999). Auditory warnings and displays: An overview. In N. A. Stanton & J. Edworthy (Eds.), *Human factors in auditory warnings* (pp. 3–30). Aldershot, UK: Ashgate.

Ulrich, R., & Miller, J. (1994). Effects of truncation on reaction time analysis. *Journal of Experimental Psychology: General, 123,* 34–80.

Viemeister, N. F., & Wakefield, G. H. (1991). Temporal integration and multiple looks. *Journal of the Acoustical Society of America, 90,* 858–865.

Wagner, E., Florentine, M., Buus, S., & McCormack, J. (2004). Spectral loudness summation and simple reaction time. *Journal of the Acoustical Society of America, 116,* 1681–1686.

Walker, B. N. (2002). Magnitude estimation of conceptual data dimensions for use in sonification. *Journal of Experimental Psychology: Applied, 8,* 211–221.

Walker, B. N. (2007). Consistency of magnitude estimations with conceptual data dimensions used for sonification. *Applied Cognitive Psychology, 21,* 579–599.

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