

Quantifying the Perceived Urgency of Missile Warning System Audio Warning

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ABSTRACT

Audio warnings are used in military aircraft to convey critical information. Missile Warning Systems (MWSs) produce audio warning sounds to alert the crew of a missile attack. To be efficient, the MWS warning sound must not only be detected by the crew but must also create an urgency to react. This paper presents an experimental study on the perceived urgency of the audio warning generated by actual MWSs installed on military aircraft. The study was also designed to determine if varying acoustical parameters of the warning sound has an effect on the perceived urgency of MWS sounds. Twenty-three volunteer listeners with normal hearing capability participated in this study. The results of this study indicated an immediate need to improve the urgency-encoding of actual MWS warning sounds and the perceived urgency of MWS warning sound can be easily manipulated by either varying the fundamental frequency or by applying a frequency modulation to the warning sound. These results will be presented and discussed in this paper.

ABOUT THE AUTHOR

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INTRODUCTION

Audio warning signals are used in a variety of environments, such as hospitals and flight decks of modern aircraft to convey critical information. In hospitals, audio warnings are used to alert staff of medical equipment malfunctions and the existence of potentially harmful medical conditions. The primary role of auditory alerts in aircraft flight decks is to direct the crew's attention to a specific critical event. Generally, audio alerts in modern aircraft flight decks are classified into three main conditions: Caution, Advisory, and Warning (CAW). Caution conditions require crew awareness, advisories provide operation status of a specific system and warning conditions require immediate crew action. In general, warning and caution conditions always produce audio warnings. When the crew hears an audio warning, the pilots must recognize the alert and analyze the meaning of it in relation to other relevant information presented in the flight deck. The goal is to resolve any abnormal or unsafe conditions. For that reason, auditory warnings represent critical cues to a possible complex situation and decision-making.

Interest in the use of auditory signals to convey critical information in human-machine interface was stimulated by the need to overcome the issue associated with overloading the human operator visual system (Cooper, 1977; DuRoss, 1978). Inherent advantages of the utilization of auditory signals over visual signals resided in the fact that they can capture users' attention regardless of where they are looking. Also, human reaction times to auditory stimulus are typically faster than to visual stimulus (Galton, 1899; Sander, 1998). The primary role of an auditory alert is to direct the operator's attention to a particular event; therefore, warning sounds must be designed efficiently according to their context and the environment in which they will be used. For example, the sound of a smoke alarm must be loud and discomforting because the goal is to provoke a feeling of the need to escape. However, this type of auditory alert is entirely inappropriate for a flight deck. Historically, audio alerts such as horns, bells, and buzzers were designed using the principle of "better safe than sorry" (Patterson, 1990). These audio alerts were generally set to be too loud and disruptive, so annoying that people turned them off rather than use them. As a matter of fact, a survey study of 50 commercial pilots showed that, in general, flight deck audio alerts were rated favorably on information, but unfavorably on the presentation style (Peryer, Noyes, Pleydell-Pearce, Lieven, 2005).

An efficient use of audio warnings in noisy workplaces is subjected to many psychoacoustics and physics constraints, particularly when the safety of the operators is concerned. The design and installation of audio alerts in noisy places is normally based on traditional practices, with limited consideration of the hearing capabilities of the operators (Tran, Héту, 1996). Two types of audio are commonly used as auditory warnings: speech and abstract tone. Speech warnings have the advantage that little or no learning is required by listeners and are suitable to convey both complex and unambiguous information (e.g., "Pull-up...Pull-up"). However, if speech warnings are used in an environment with a high level of background noise, they are susceptible to masking. Masking is a condition in which a noisy condition reduces the detectability of another sound. Abstract tones, on the other hand, are less likely to be masked by the background noise and are capable of conveying the required information quickly. However, there are also problems associated with using abstract tones. In many instances, auditory alerts are poorly designed and installed. For example, every year accidents occur in noisy workplaces because audio alerts were not heard (Wilkins, Acton, 1982). In contrast, there are situations where audio alerts are too loud and distracting. Besides the detectability issue, little attention has been given to the perceived urgency aspect of audio alerts. They are designed and installed with little consideration to their specific usage goal, which is to convey the correct information. This situation leads to the issue of a serious mismatch between the perceived urgency of the warning and its real situation urgency. Another disadvantage of abstract tones is the difficulty associated with learning and remembering a large set of warning sounds (Patterson, Milroy, 1980; Meredith, Edworthy, 1991). Regarding the efficiency of aircraft cockpit warning sounds, the Federal Aviation Administration (FAA) crew alert guidelines (DOT/FAA/RD-81/38II) specified the following:

- Should attract the crew's attention, enable them to determine the *urgency*, identify the problem, provide feedback and enable monitoring of aircraft status.
- Should *minimize* demands on crew *information processing* and *memory*.

The purpose of the experiment in this study is to quantify the perceived urgency of the MWS audio warnings and to determine if varying the frequency or frequency modulation of the MWS warning sound has an effect on the perceived urgency. In this study, we are focusing on a very specific type of audio warning: Missile Warning System audio warning. The MWS is part of the avionic package on military aircraft and is installed to detect attacking missiles. When a missile is detected, the MWS automatically displays a visual cue to indicate the direction of arrival (DOA) of the missile and generates an audio alert to the crew. The purpose of utilizing a combined alert, auditory and visual, is to provide a redundancy of information. A busy crew not looking at the display may miss the visual cue, but not the aural cue. Also, in the case of a malfunctioning display device, audio cue is still there to alert the crew of a dangerous situation. This critical warning requires the crew to make an *immediate* defensive maneuver and deploy the available countermeasures to disrupt missile tracking.

PERCEPTION OF URGENCY

What is urgency? Urgency can be defined as a *sense of requiring immediate attention or action*. Therefore, if an auditory warning is used to alert of a dangerous condition, it must create some degree of urgency to the listeners. In other words, an audio warning is efficient when it increases the probability of an appropriate action under an urgent condition (Guillaume, Pellieux, Chastres, Drake, 2003).

It is not known exactly what in the sound determines how urgent it will be perceived. However, we do know that the perceived urgency can be manipulated by varying acoustical parameters of the sound. One of the most important physical factors of an audio warning to convey the sense of urgency is the intensity of the audio signal. The perception of urgency increases in proportion to the signal intensity (Loveless, Sanford, 1975). However, in critical environments, such as intensive care or aircraft flight decks, the intensity of the audio warning can vary only within a very narrow scale. If the audio signal is too weak, it will be undetected, and if it is too loud, it will be perceived as disruptive or aversive and can increase the level of stress during the warning (Doll, Folk, Leiker, 1984). For that reason, even if the intensity of the warning sounds plays a major role in the perceived urgency, it can only be controlled systematically. Indeed, if the flight deck's auditory warning system volume is set too loud, some pilots have reported that their initial response to the alert is to find a way to silence the warning sound instead of processing the audio warning for its meaning. Several investigators who have studied the design of audio warnings have pointed out that acoustic parameters of the sound, such as frequency, repetition rate, amplitude, and frequency modulation index, may be varied independently to generate audio alerts that convey different levels of urgency (Patterson, 1982; Edworthy, Loxley, Dennis, 1991; Hellier, Edworthy, Dennis, 1993).

How can the perceived urgency be quantified? The perceived urgency can be assumed as an attribute of the audio warning (Burt, Bartolome, Burdette, Comstock, 1995). For this reason, it can be quantified even if the listener does not know the meaning of the warning. This is important because audio warnings can be designed and installed to alert of urgent situations without requiring operators to go through any learning or training session. Audio warnings cannot be effectively designed without taking into account the capability of the human auditory system. Acoustic parameters of audio warnings, such as *intensity*, *spectral content*, or *temporal pattern*, are acoustical parameters that can be adjusted, while *loudness*, *localization*, or *urgency* are psychoacoustic factors perceived by the human auditory system. Manipulating the acoustical parameters of the audio warning has a direct effect on psychoacoustic factors. The subjective change (e.g., perceived urgency) with respect to an objective change (e.g., an acoustic parameter) can be expressed use Steven's psychometric function (Steven, 1957):

$$S = kO^n \quad (1)$$

Equation (1) quantifies the extent to which an objectively measurable change in a stimulus value O produces a change in the subjective judgment S. The constants k and n are specifics to the objective (e.g., an acoustic parameter) and subjective factor (e.g., perceived urgency) expressed in the equation.

COGNITIVE FACTOR

Is there a link between the acoustic properties of an audio alert and the mental presentation of it? A series of parallel experiments was performed with pilots using (i) synthesized warning sounds designed with the prescription of Edworthy et al. (1991) to convey the perception of increasing urgency by varying one or more acoustic parameters, and (ii) recording of actual aircraft warning sounds (Guillaume, Pellieux, Chastres, Drake, 2003). The results obtained from experiment (i) validated the notion that perceived urgency can be varied by manipulating acoustic parameters. However, this result was not entirely observed with actual recorded warning sounds in the experiment (ii). Although the acoustic parameters of a number of warning sounds were expected to have the pilots perceive them as very urgent, they were judged as non-urgent events or vice-versa. The results of this experimentation seem to indicate different complex processes involved in the perception of urgency. These processes seem related to whether the warning sound evokes a mental presentation or not. When a mental presentation exists, hearing the warning sound brings the mental presentation to mind immediately, therefore, judging whether it is an emergency situation is dependent on the association made by the subjects between their mental associations evoked by the audio sequence (Guillaume, 2011).

For instance, if the pilots were trained to associate a cockpit warning tone to a specific event, when the warning is heard, they may be able to immediately associate it to an urgent situation. This automatic processing probably comes from personal experience and/or training. On the other hand, when a mental presentation doesn't exist, the perceived urgency is solely judged from the acoustic property of the warning sound.

PREVIOUS STUDIES

Assessing the effectiveness of auditory warning signals is a complex task. However, we can assume that auditory alerts are efficient only if they are *detectable* in an environment with or without background noise, are *recognizable* among other sound signals, and attract attention by producing some degree of *urgency*.

The problem of *detectability* of audio warnings in a noisy environment has been the subject of numerous studies. The detectability of any sound in a noisy environment is determined by the masked threshold. The masked threshold represents the minimum level of intensity of the audio warning that can be detected in a background noise and is a direct function of the critical bandwidth of the human auditory filtering system. Human capability of signal detection in a competitive background noise can be measured and determined by various clinical tests (Tran, Héту, Laroche, 1991). To ensure the detection of an audio warning, Patterson's guidelines for aircraft auditory warning design proposed that the level of intensity must be at least 15dB sound pressure level (SPL) greater than the masked threshold, but no more than 25dB SPL because there is no extra gain (in term of detectability) by making the audio warning too loud. Another model that can be used to properly adjust the warning intensity was proposed by Laroche, Tran and Héту (1991). Their computerized model was based on the concept of the excitation pattern that would occur at the level of the ear when a warning sound was presented in a noisy place. The model was based on the estimation of the critical bandwidth (Zwicker, Scharf, 1965) of the auditory filter system; therefore, it has the capability of taking into account the deterioration of the detection capability due to age or to noise-induced hearing loss of the listeners. This model was successfully used to adjust the intensity of audio warnings installed in many noisy workplaces.

Guidelines for the ergonomic design of auditory warning signals have been proposed (Sorkin, 1987). They comprise a set of rules that help determine appropriate signal parameters, such as the sound pressure level, the spectral content, and the temporal pattern of warning signals. It is recommended, in particular, to use temporal sequences of pulses to facilitate signal recognition. A complete study on the effectiveness of auditory warning sounds was performed for the application to commercial aircraft flight deck (Patterson, Mayfield, 1990). These authors demonstrated that audio warnings can be ergonomically designed using a structural hierarchy composed of a base unit: a pulse of sound with duration between 100 and 300 msec. This basic unit pulse of sound is then repeated several times at different levels of intensity, pitch, and interval. The resulting sequence represents a burst of sounds. The complete warning can be formed using these burst of sounds separated by silence intervals. The temporal characteristic of a warning sound designed using this principle defines its distinctive character. Studies using warning

sounds designed this way reported that it improved the ability to *learn* and *recognize* the meaning of the warning sounds.

Finally, many studies demonstrated that there is a strong correlation between the warning sound acoustical parameters and the perceived *urgency* (Edworthy, Loxley, Dennis, 1991; Burt, Bartolome, Burdette, Comstock, 1995). The results of these studies clearly demonstrated that a wide variety of acoustic parameters have consistent effects on the perceived urgency of warning sounds. They also showed that it is possible to manipulate a single acoustic parameter of the audio warning to change the perceived urgency. One of the most important applications of the studies' results is the ability to change the degree of urgency of an existing critical audio warning, such as an MWS audio warning, by altering its acoustics parameters. For example, a simple change of the duration of the warning or altering the spectral content by varying the modulation index may increase the degree of urgency. Another implication of these results is that it is now possible to design audio warnings with a specific degree of urgency in relation to the situational urgency. Therefore, we can match the most urgent audio warning to the most urgent situation and so on. Such work was demonstrated experimentally for operating and recovery rooms (Montahan, Tansley, 1989).

Edworthy, Loxley, and Dennis (1991) identified several acoustic parameters that can be manipulated to vary and predict the perceived urgency of warning sounds. They can be summarized as follows:

1) Concerning the pulse parameters of the warning.

- Urgency increases when the fundamental frequency of the pulse is increased.
- Urgency increases when the degree of irregularity of the harmonic series is increased.
- Standard amplitude envelope of the pulse is perceived as being more urgent than a pulse with slow onset and offset ramp.

2) Concerning the burst parameter of the warning.

- Urgency increases when the speed of the bursts is increased. The speed is controlled by varying the delay between pulses.
- Urgency increases when the number of pulses is increased.
- Regular rhythm is perceived as been more urgent than a syncopated rhythm.
- Frequency spectrum tends to have a strong correlation with the perceived urgency.

LISTENING EXPERIMENT

Magnitude estimation and pairwise comparison experiments were conducted to quantify the perceived urgency of MWS warning sounds.

Participants

Twenty-three volunteers participated in the listening experiment. They were asked and none of the participants reported having a history hearing problems. They were subdivided into two groups: 7 listeners were former military pilots and 16 were non-pilots. We assumed that non-pilot listeners have limited exposure to cockpit audio warnings, therefore urgency will be solely judged from the acoustic properties of the warning sound. On the other hand, the pilot group will provide important information about the role of the cognitive factor on the perceived urgency.

Stimulus

Missile Warning System audio warnings are used to alert the crew of a missile attack; therefore, it is obviously one of the most critical warning sounds of the flight deck. The main objective of this study was to quantify the perceived urgency of this type of audio alert. Additionally, we want to determine if there is an easy way to increase the urgency of this type of audio warning by varying one of the acoustic parameters, such as the frequency, or the index of modulation. We also want to determine if learning or training have an effect on the perceived urgency of the MWS warning sound. The selection of the warning sounds used in this study was based on these objectives.

MWS AAR-47 is a Missile Approach Warning System used on slow moving aircraft, such as helicopters and military transport aircraft, to notify the crew of a short-range missile attack. On modern military aircraft, the MWS AAR-47 is normally integrated into the main avionics interface bus of the airplane and is controlled by a Mission Computer (MC). In this integrated configuration, the MWS audio warning is managed and produced by the MC. However, in the legacy configuration, the AAR-47 MWS is installed on the airplane as a stand-alone subsystem. The MWS audio warning sound is normally generated from the control panel and routed to the pilot headset via the intercom system. In this study, we used the MWS audio warning sounds generated from both configurations. A total of six warning sounds were used in this study. All audio warning sounds were synthesized and generated from an Electronic Warfare (EW) simulation package:

- 1- **MWS1**: AAR-47 MWS audio warning as installed in a legacy configuration. This audio warning is produced from the MWS control panel.
- 2- **RWR MSL**: Radar Warning Receiver “Missile Launch” audio warning. This warning alerts the crew when the RWR detects a radar threat and has just switched to the missile guidance mode.
- 3- **MWS FM1**: Derived from MWS1 by applying a Frequency Modulation with a low index of modulation.
- 4- **MWS FM2**: Derived from MWS1 by applying a Frequency Modulation with a high index of modulation.
- 5- **MWS FREQ**: Derived from MWS1 by modifying the fundamental frequency of the pulses.
- 6- **MWS2**: AAR-47 MWS audio warning as installed in an integrated configuration. This warning is produced by the MC.

Table 1 provides the description of the audio warnings used in this study.

Table 1. Characteristic of the Audio Warnings Used in the Listening Experiments

Audio Warning	Description	Acoustic Characteristic
MWS1	AAR-47 MWS warning sound: legacy configuration	Square wave. Two pulses of sound separated by a delay of D1. Fundamental frequency of the first pulse is F1 and the second pulse is F2. Repeated three times.
RWR MSL	RWR-69 Missile launch warning sound – legacy configuration	Seven beeps of fundamental frequency F3.
MWS FM1	MWS1 with frequency modulation	FM = 20 Hz. Index of modulation = 2.5
MWS FM2	MWS1 with frequency modulation	FM = 20 Hz. Index of modulation = 10.0
MWS FREQ	MWS1 with frequency fundamental of each pulse multiplied by a factor of 2	Square wave. Two pulses of sound separated by a delay of D1. Fundamental frequency of the first pulse is 2*F1 and the second pulse is 2*F2. Repeated three times.
MWS2	AAR-47 MWS warning sound: integrated configuration	Square wave. Fundamental frequency F4. Repeated for 3 seconds with a delay of D2.

Experiment design

Two experiments were designed to study the perceived urgency of MWS warning sounds. The following instruction was provided to the participants at the beginning of the listening session: “*You will be asked to listen to a few warning sounds. Your task is to judge the level of urgency when you listen to each of them. Urgency is defined as a sense of requiring immediate action*”.

To avoid any bias in urgency judgment, participants were not told about the type of audio warnings (e.g., MWS) the study employed. During the listening experiment, the name of each audio warning was replaced by an alphanumeric term (e.g., 1A). The study was divided into two experiments. The first experiment was the magnitude estimation process, in which the participants were asked to listen to each warning sound, and assign a numerical value expressing the perceived urgency on a scale of 0 to 100, with “0” being characterized as “the most non-urgent possible sound” and “100” being characterized as “the most urgent possible sound”. The exact instruction was as show in Figure 1:

Experiment 1

- Listen to each warning sound.
- You are required to rate how URGENT you felt the warning.
- Use a rating scale from 0 to 100. A rating of 0 means the warning was NOT urgent at all and 100 means the warning was EXTREMELY urgent.
- There is no right or wrong answer. Simply rate the warning indicating how urgent you feel when you listen to the sound.
- Rate the warning sounds in the list from the top to the bottom.
- Replay the warning if required.

Figure 1. Instruction for Experiment 1

In the second experiment, referred to as the pairwise comparison task, participants were asked to listen to a pair of warning sounds. All audio warnings used in Experiment 1, except for the MWS2 audio warning, were used in this pairwise comparison session. For five audio warnings, there will be $\frac{n*(n-1)}{2} = \frac{4*5}{2} = 10$ pairs of audio warning sounds to judge. The participant’s task was to select the most urgent warning sound of the pair. The exact instruction was as shown in Figure 2:

Experiment 2

- Listen to each pair of warning sounds.
- Choose the most urgency between the two and report your selection.
- There is no right or wrong answer. Simply rank the warnings indicating how urgent you feel when you listen to the sounds.

Figure 2. Instruction for Experiment 2

Finally, each participant was asked if they could recognize or identify any warning sound in the experiments, because recognition of the tested warning sounds may indicate a bias of perceived urgency judgment.

Listening procedure

A listening test and an answering sheet were distributed to each participant. Participants performed the listening test using their own desktop or laptop computer. They were also instructed to use a headset to perform the test.

The listening test was designed using MS PowerPoint. The test contained instruction and links to the tested warning sounds. The participants were first instructed to listen to a calibration tone (Pure tone of 500 Hz) and adjust their computer volume to a comfortable level. For the magnitude estimation experiment (Experiment 1), a random order

of the six warning tones was presented to the listeners. For the pairwise comparison (Experiment 2), all possible pairs derived from the five warning sounds were presented to the listeners in a random order.

EXPERIMENTAL RESULTS

1- Experiment 1: Magnitude Estimation

The results of the magnitude estimation experiment are reported in Table 2. The first two columns show the rating mean and standard deviation of all participants.

Table 2. Results of the Urgency Judgement From the Magnitude Estimation Listening Experiment

Audio Warning	Mean	SD	Z-Score	Rank Mean (SDEV)
MWS1	59.48	16.68	-0.029	3.53 (1.11)
RWR MSL	42.30	19.01	-0.718	5.00 (1.03)
MWS FM1	77.78	17.68	0.585	2.06 (1.00)
MWS FM2	79.74	21.38	0.784	1.82 (1.30)
MWS FREQ	64.96	16.94	0.191	3.29 (1.23)
MWS2	39.96	27.61	-0.812	5.00 (1.22)

The rating results showed that participant ratings of perceived urgency were distributed well across the rating scale (0 to 100). However, we observed that some participants tended to use the extreme portion of the scale to make their urgency rating. Additionally, we observed a few outlier ratings predominantly from the first warning sounds of the test, suggesting that these participants changed their urgency rating with familiarization to the scale. To avoid biases from these outliers, each participant's ratings were converted to Z-score. Mean Z-scores are reported in Table 1.

Finally, the ranking of the warning sounds was derived using the urgency rating scores of each participant. The warning sound with the highest rating was assigned a ranking of "1," the next highest rating was assigned a ranking of "2," and so on. When two or more ratings were equal, the average ranking was computed and assigned to each warning sound. The mean ranking and standard deviation (in parentheses) of each audio warning are presented in Table 2. In summary, the results obtained suggested the following ranking: MWS FM2 represented the warning sound with the most perceived urgency, followed respectively by MWS FM1, MWS FREQ, MWS1, and RWR MWSL. The audio warning MWS2 sound was perceived as the least urgent.

Kendall's coefficient of concordance computed with the obtained ranking scores was $W=0.5176$ ($p < 0.001$). This result indicates a good agreement between our participants when they rank the perceived urgency of the tested audio warning sounds.

2- Experiment 2: Pairwise Comparison

The result of the pairwise comparison experiment was compiled and reported in the preference matrix as presented in Table 3.

Table 3. Preference Matrix Obtained from the Pairwise Comparison Experiment

	MWS1	RWR MSL	MWS FM1	MWS FM2	MWS FREQ	SUM
MWS1	-	17	4	3	4	28
RWR MSL	6	-	3	4	4	17
MWS FM1	19	20	-	7	18	64
MWS FM2	20	19	16	-	20	75
MWS FREQ	19	19	6	2	-	46

In this experiment, our 23 participants compared the perceived urgency of a total of 10 pairs of audio warning sounds. For each pair of warning sounds, the preference matrix shows how many participants actually chose one

specific warning sound as the most urgent against the other warning sound of the pair. For instance, when comparing MWS1 and RWR MSL, 17 participants selected MWS1 as the most urgent warning sound of the pair, and 6 participants selected RWR MSL as the most urgent. The last column of the table shows the total number of time that a specific warning sound was selected as the most urgent when compared to the other warning sounds.

Kendall's coefficient of concordance computed from the obtained ranking of this experiment is significant ($W=0.4404$, $p<0.001$) and indicates a good agreement of our participants in this pairwise comparison task.

From the obtained results, we can conclude that the MWS FM2 audio warning sound was selected as the most urgent by the majority of the participants when compared with other warning sounds. The ranking as obtained from this experiment is MWS FM2 as the most urgent, followed by MWS FM1, MWS FREQ, MWS1, and RWR MSL as the least urgent. This result is consistent with the results obtained from the magnitude estimation task. The Spearman's rank order correlation between the two methods of ranking was significant ($\rho = 0.769$, $p<0.001$). Therefore, these measures suggest that the judgments made collectively by our participants in the two listening experiments were very stable. The perceived urgency of the warning sounds, as judged by our participants in the magnitude estimation task, is very consistent with the one observed in the pairwise comparison task.

3- Cognitive factor

Each participant was asked if they recognized any of the audio warning sounds. Two pilot participants did effectively recognize and identify correctly the MWS2 and RWR MSL audio warnings. Two other pilots answered the question positively on MWS1, MWS2, or RWR MSL, but they wrongly associated the audio warnings with other events, such as a stabilizer warning, low engine RPM, or low rotor RPM. Finally, three pilots said they do not recognize any of the audio warning sounds. *Can the recognition of a specific warning sound affect the perceived urgency, regardless if it was correctly or wrongly associated with the event?* To answer this question, the magnitude estimation results obtained for the pilot group were separated and then compared with the non-pilot group. Table 4 shows the unpaired t-test result for each warning sounds.

Table 4. Descriptive Statistics and Results of the Unpaired t-test for Urgency Rating Between Pilot and Non-Pilot Groups

	Pilot			Non-Pilot			Un-paired t test		
	Mean	SD	n	Mean	SD	n	t	p	SE
MWS1	72.86	10.35	7	53.63	15.65	16	2.9598	0.0075*	6.497
RWR MSL	60.71	17.90	7	34.25	13.20	16	3.9729	0.0007*	6.660
MWS FM1	77.14	18.68	7	73.75	17.75	16	0.4151	0.6823	8.166
MWS FM2	73.57	27.65	7	82.44	18.41	16	0.9121	0.3721	9.725
MWS FREQ	72.14	9.06	7	61.81	18.79	16	1.3730	0.1894	7.524
MWS2	56.43	27.65	7	32.75	25.11	16	2.0206	0.0530	11.719

* $p<0.05$

According to the Table 4, the perceived urgency rating for the MWS1 and RWR MSL audio warning was statistically different ($p<0.05$) between the pilot and non-pilot groups. Therefore, for a reason yet to be explained, the pilots seem to assign a higher rating to these two warning sounds when compared to the non-pilot group.

DISCUSSION

The results of this study indicate that our participants rated the perceived urgency of actual MWS audio warning sounds with a high level of consistency in both listening experiments. The ranking obtained from the magnitude estimation task was perfectly correlated to the one obtained with the pairwise comparison task. The major findings in this study can be summarized as following:

- 1- The perceived urgency of actual MWS audio warning sounds (MWS1, MWS2, and RWR MSL) was rated on the low side of the mean as showed by their negative Z-scores.
- 2- We tested how the perceived urgency was affected by varying the acoustic parameters of the sound. For this purpose, we modified the MWS1 warning sound by varying separately two acoustical parameters: we double the

fundamental frequency and we applied a frequency modulation to MWS1. In both cases, the perceived urgency increased for both groups of participants. Additionally, for the case of frequency modulation, the perceived urgency tends to increase with the index of modulation (perceived urgency of MWS FM2 was rated greater than MWS FM1). The increase of urgency with respect to the index of modulation can be explained by Steven's psychometric function described in the equation 1. When plotted on log-log axes, "n" is the slope of the psychometric function and it represents the rate of change of the perceived urgency. The value of "n" is specific for each acoustical parameter. For example, Hellier's study (1993) found the value of "n" for speed and repetition was 1.35 and 0.502, respectively. The sample of data in this study was too small to allow us to quantify the value of "n" for the index of frequency modulation.

- 3- The pilot group tended to assign a higher degree of urgency to the MWS1 and RWR MSL warning sounds. The data sample in this study (only seven pilots) was too small to make a conclusive observation, but it may be explained by the fact that some pilots recognized these warning sounds and associated them with some kind of urgency events. Indeed, it may be reasonable to think that pilots are more alert when they hear and recognize warning tones; this is similar to the situation that nurses are more alert when they hear warning tones generated from medical equipment. Similar observations were already reported in some studies (Patterson, 1982; Momtahan, Héту, Tansley, 1993). The authors of these studies noted that operators have the capability to learn, retain in the memory, and associate a specific event to a specific warning sound. When hearing a specific warning sound, they can bring back the mental presentation associated to this warning sound immediately. Nonetheless, as Patterson and Milroy (1980) observed in their study, learning and retaining auditory warning has its limitation. Operators are usually capable of learning up to five or six warnings; however, beyond that point, it is very difficult to commit new warning sounds to the memory.

Besides the issue of the perceived urgency of warning alerts, there is also a concern to map the degree of urgency of a specific warning sound to the priority urgency situation it was designed for. For example, an MWS warning alert must be perceived more urgent than the one that announced an unimportant system failure. For this reason, warning sounds must be designed and integrated to the flight deck as a whole, especially when this warning sound is used to alert the crew of a critical situation, such as missile attack. Unfortunately, it is very difficult or impossible to take into account all the existing auditory warnings of the flight deck as a whole when integrating a legacy MWS or any other legacy electronic warfare subsystem to the flight deck. In this situation, we are facing two main issues. First, the perceived urgency of the warning tone may not be appropriate, and second, the urgency mapping of this MWS warning sound with others cockpit audio alerts is almost impossible. A proper familiarization and recognition training of the MWS warning sound for the crew is then recommended.

CONCLUSION AND DIRECTION FOR FUTURE WORK

The perceived urgency of actual Missile Warning System warning sound was quantified in this study. The results indicate an immediate need to improve the urgency-encoding of actual MWS warning sounds. The MWS warning sounds were perceived to be far less urgent than the event dictates, especially for the RWR MSL. Additionally, it is possible to manipulate the perceived urgency of the legacy MWS warning sound by either varying the fundamental frequency or by applying a frequency modulation to the warning sound.

Two additional observations from this study provided direction for future work on the perceived urgency of flight deck audio warning of MWS and other Electronic warfare equipment, such as RWR or Laser Warning System (LWS):

- 1- Cognitive factor may play an important role because the pilot participants tended to rate the perceived urgency of the MWS warning sounds higher than our non-pilot participants. A training program dedicated to the learning and retaining of flight deck MWS warning sounds for military pilots could be beneficial. Should such training be added to the pilot training curriculum?
- 2- It is important to note that in this study, our participants rated and ranked warning sounds without performing any competitive tasks. There are indications that perceived urgency may deteriorate when operators are subjected to additional workloads (Guillaume, Pellioux, Chastres and Drake, 2003).

Synthetic environments, such as a flight simulator, provides an ideal tool to satisfy the above recommendations. Besides the obvious fact that a flight simulator is an asset for training, it can be also used to test, improve, and design efficient MWS audio alerts because they can realistically reproduce the combat environment and the

workload that military pilots are subjected to during a real mission. Additionally, hostile threats can be easily simulated and controlled in this environment. The perceived urgency can then be quantified under more realistic conditions, including the crew's workload.

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