Effect of Sound Cue Frequency Filters on Front/Back Localization Performance for Three-Dimensional Verbal and Non-Verbal Warnings

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EFFECT OF SOUND CUE FREQUENCY FILTERS ON
FRONT/BACK LOCALIZATION PERFORMANCE FOR THREE-DIMENSIONAL
VERBAL AND NON-VERBAL WARNINGS

By:
Angelica A. Hernandez

A Graduate Thesis Submitted to the Human Factors and Systems Department in Partial
Fulfillment of Requirements for the Degree of the Master of Science in Human Factors and Systems

Embry Riddle Aeronautical University
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EFFECT OF SOUND CUE FREQUENCY FILTERS ON
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Angelica A. Hernandez

This thesis was prepared under the direction of the candidate's thesis committee chair, Dr. Shawn Doherty, Department of Human Factors and Systems, and has been approved by the members of her thesis committee. It was submitted to the Department of Human Factors and Systems and was accepted in partial fulfillment of the requirements for the degree of Master of Human Factors and Systems.

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ABSTRACT

In aviation, as technology becomes more advanced and more demands are placed on the human operator, warnings have become an important part of display design. Although warnings have made a significant contribution to safety, problems still plague their design. Recent technological advances have been able to give sounds and warnings a three-dimensional quality (3D). This technology enables a person to perceive sound from any direction around the listener without having the sound physically come from that direction. Three-dimensional sounds have been shown to improve target acquisition and collision avoidance in flight (Oving & Bronkhorst, 1999), and may have other future applications as well. However, one of the main drawbacks of using 3D audio technology is the increase in front and back localization errors in which a listener may confuse the location of the warnings. Mistakes in localization may be dangerous in flight, especially when locating such hazards like air traffic.

This study compares both verbal and non-verbal warnings, which have not been previously compared in previous research. The purpose of this study is to determine whether or not altering the frequency content of auditory warning signals could affect the localization performance for forward and backward presentation of the signals. The results confirmed previous research conducted by Ehmann (2001) which found that altering the frequency content did not affect localization performance. There were differences found between warning types, which indicate that future research may need to be conducted on the difference between the warnings with respect to how they are localized.
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INTRODUCTION

In aviation, as technology becomes more advanced, and more demands are placed on the human operator, warnings have become an important part of display design. Warnings may alert the pilot of problems such as traffic flow, conflicts with terrain and landmarks, or mechanical malfunctions of the aircraft (Noyes, Kazem & Phyo, 2000). No one can deny the fact that auditory warnings have increased safety in all industries, especially aviation (Wickens, 2003). However, as technology becomes more complex the warnings and alerts in the system will also have to be upgraded to suit the needs of the pilot. Typically warnings are presented in either verbal or non-verbal form (or a combination of both), each of which is used for different kinds of tasks and in different contexts (Wolgalter, Conzola & Smith-Jackson, 2002). Some research (Salvendy, 1987) has found that verbal and non-verbal warnings are each better suited for certain types of tasks, but minimal literature exists that compares the two. The following study explores differences between verbal and non-verbal warnings, and a person's ability to locate or localize them both. This study attempts to establish frequency content as a valid consideration for adequate three-dimensional auditory display design.

Over the past decades sound technology has made it possible to add another dimension to warnings and sound cues that have not been previously available in conventional warning systems. Utilizing knowledge about the human auditory process and physical properties of sound, it is now possible to add a spatial aspect to a warning or alarm (Bronkhorst, Veltman & Van Breda, 1996). Sounds can now appear to be emanating from any direction around the listener without having to physically come from that direction by utilizing speakers, headphones, or three-dimensional (3D) sound.
software. The ears may be tricked into thinking that sound is coming from any direction thus giving it a spatial quality (Bronkhorst, Veltman & Van Breda, 1996).

Most of the research being conducted for 3D sound technology has been centered on learning how well 3D audio displays can aid a person to discern sounds from many directions. Using a 3D audio display a person is able to localize sounds with some accuracy about the front and peripheral area around the person's head (Bronkhorst, Veltman & Van Breda, 1996; Stanton & Edworthy, 1999). However, it has been shown that substantial errors in front/back localization can occur (Wightman & Kistler, 1997; Middlebrooks, 1997). Causes for these errors have been attributed to the human localization process and the way the technology manipulates sound characteristics.

This study measures the sound localizability of 3D verbal and non-verbal warning sounds. This study also investigates how altering the physical properties of sound cues may degrade localization performance specifically for the front and back regions as well as show significant differences in localization performance for verbal and non verbal warnings. This study was in part based on a previous study conducted by Ehmann (2001) that focused on reducing front and back errors for a non-verbal helicopter sound clip. The intent is that the present study may extend Ehmann's findings to include actual verbal and non-verbal warnings that are used in a real cockpit environment. By extending Ehmann's research this study examined how frequency content could be an adequate cue for the future development of 3D cockpit warnings.

Auditory Warnings

Over time, the use of auditory warnings has increased as technology and sophistication of the systems also have also been upgraded, especially in aviation. This
can be seen in the difference between earlier versions of aircraft, which have analog 
gauges, when compared to later versions. For example, there are 172 warnings on a DC8 
in comparison to 418 on a DC10 (Noyes, Kazem & Phyo, 2000). This increase in the 
amount of warnings creates an increase in demands on memory and attention for the 
pilots in the cockpit and also establishes the importance of appropriate warnings design 
(Stanton & Edworthy, 1999).

Cockpit warnings alert pilots when there is a situation that requires their 
immediate attention, such as an emergency situation or when the cockpit environment 
changes. Auditory Warnings may be sirens, horns, bells, buzzers, klaxons, or words 
spoken by a speaker (Stanton & Edworthy, 1999). The issue of appropriate design, 
however, is not always clear and researchers are split on what may constitute a "good" 
design. For instance, the surrounding environment as well as the context of the situation 
when the warning goes off is a major consideration for auditory display designers.

Although Woodson, Tillman and Tillman (1992) suggest that tones or speech warnings 
may be used in certain contexts, Stanton & Edworthy (1999) suggest that there is no 
indication that specific sounds should be dedicated to certain circumstances, as seen in 
Table 1. Different sounds may used for a variety of tasks, and they are not limited to just 
one event. A warning's environment and the circumstances present should be thoroughly 
explored if it is to be designed appropriately.

The issue of training also may have an impact on the design of warnings. People 
are able to attach meaning to the different kinds of warnings through exposure to them or 
with occasional training. For instance, depending on the type of buzzer, a person can 
normally tell if the sound they hear is telling them that a fire is near or that need to wake
up in the morning. Using the proper timing and tone is also another issue explored by researchers that is essential to good warning design (Woodson, Tillman & Tillman, 1992; Stanton & Edworthy, 1999). Adjustments made to timing and speed of can alter how the warnings is perceived (Wolgalter, Conzola & Smith-Jackson, 2002).

The problems generally associated with typical warning displays are that often designers install too many of them. They are often too loud, startle people, frequently activate unnecessarily, and are installed in inappropriate environments. For example, speech may not be the right choice to use in noisy areas where sentences may become distorted or cannot be heard. Problems associated with speech warnings tend to be degraded quality or intelligibility (Patterson, 1983). Table 1 compares different strengths and weaknesses of speech and non-speech signals.
<table>
<thead>
<tr>
<th>Type</th>
<th>Strengths</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speech</td>
<td>• Good for rapid communication&lt;br&gt; • Can convey useful information&lt;br&gt; • Meaning intrinsic in message&lt;br&gt; • Minimal training required</td>
<td>• May go unnoticed&lt;br&gt; • Easily masked or distorted&lt;br&gt; • Problems with dialects, accents&lt;br&gt; • Intelligibility may be a factor&lt;br&gt; • Not good for events requiring memory</td>
</tr>
<tr>
<td>Tones (periodic or non-periodic)</td>
<td>• Unidirectional&lt;br&gt; • Continuous and attention getting&lt;br&gt; • Good for events that don’t occur often&lt;br&gt; • Common warnings do not require training</td>
<td>• Only 5-6 tones can be recognized&lt;br&gt; • Difficulties in localization&lt;br&gt; • Give limited information with out training</td>
</tr>
</tbody>
</table>

(Compiled from Woodson, Tillman & Tillman, 1992; Stanton & Barber, 1999)

Sanders and McCormick (1987) also provide some useful guidelines to designing auditory warnings. These guidelines center on the fact that each warning must be suited for each environment. For example, warnings should be discernable from other auditory signals and noise. Typically warnings should be 15 decibels above the ambient noise, or the naturally occurring noises in the environment (Patterson, 1983). In aviation, this means that the pilot should be able to notice when a warning goes off in the presence of the ambient noise, such as engine noise or radio communication. This design requirement frequently translates into a common problem associated with warnings, which is that they are too loud. Excessive noise can startle and become a stressor, which may lead to performance decrements or may even compromise communication amongst
crewmembers. Crew may be too focused on the sound instead of flying the aircraft (Noyes, Kazem & Phyo, 2000; Stanton & Edworthy, 1999).

A second guideline suggests that signals should not overload the pilot with unnecessary information. Other modalities, such as visual displays or prior knowledge should provide the necessary information over what to do next in case of an emergency (Sanders & McCormick, 1987; Stanton & Edworthy, 1999). Another important guideline is that each warning should be different and shouldn't be confused with all other warnings that are in the system (Sanders & McCormick, 1987).

New technological advances have also allowed a spatial aspect to be placed on warnings. Current warnings are omi-directional, or are not specifically emanating from a specific direction. By adding a spatial aspect to warnings the warnings themselves can be heard and perceived as coming from different directions. Adding this characteristic to a sound may produce more meaningful warnings by creating a separate cue to enhance memory or retention. If necessary, more flight related information could ideally be given to the pilot because he or she would have more help to remember it. This however, adds another issue to appropriate warnings design. If 3D cockpit warnings are to be implemented into the cockpit it is important to adequately design them so that they are detectable and localizable. Current research in aviation has focused on applying 3D displays to flying and cockpit warnings. Adding a spatial aspect to warnings has been found to aid pilots in avoiding traffic while flying (Oving & Bronkhorst, 1999). Three-dimensional sound cues are added in conjunction with the Traffic alert Collision Avoidance System (TCAS) so that the pilot may detect conflicting traffic quicker and more accurately.
Three-dimensional warnings allow the ears to unburden the visual system of some of the attention demanding tasks, by giving the pilot an extra modality to rely upon (McKinley, Erickson & D'Angelo, 1994). While adding a spatial aspect to warning signs may increase detection and performance, a better understanding for the reasoning behind the increase may be found in the brain. The composition of sounds and how they are localized and processed has a great impact on user response to warnings.

Sound Localization and Auditory Warnings

"The ability to localize a sound source is an evolutionary prerequisite for animals' (including humans) survival (Withington, 1999)." In the natural environment locating sound not only helps us detect where objects are but also allows us to navigate through the environment. Localization is the ability of a person to discern from what location a sound is coming from in an environment (Withington, 1999; Middlebrooks, 1997). Humans are able to localize sound because of differences in the physical aspects of the sounds that reach the individual ears (Wightman & Kistler, 1997).

Sound waves are the physical vibrations of air molecules (or water molecules) that are the stimuli that produce the sensation of hearing sound (Goldstein, 2002). As a sound travels through the air, the intensity at which it is heard, or even the pitch or frequency of the sound may change. The sound waves are transformed and changed by interacting with objects in the environment or with the listener themselves, depending on the location of the source. Pitch is a perceptual quality that describes how "high" or "low" a sound it. Frequency describes the actual physical properties of the pitch of the, or the actual amount of times the molecules will vibrate. Frequency is measured in hertz, and humans can hear frequencies between 20 and 20,000 hertz (Goldstein, 2002). Most sound
that can be heard is complex and is composed of many combined frequencies. Studies have reported that humans are very good at locating sounds in the environment and only have an average error of around five degrees plus or minus from the actual position (McKinley, Erickson & D'Angelo, 1994; Wightman & Kistler, 1997; Withington, 1999). How in fact the listener localizes the sound has been suggested by theories of hearing.

*The Duplex Theory*

Conventional theories of sound localization have involved timing and intensity differences. The most accepted theory to explain this phenomenon is Duplex theory. Duplex theory states that sound cues are localized based on both interaural time differences (ITDs) and interaural level differences (ILDs). Interaural differences occur because sounds from different positions in space will reach each ear at different times due to the spatial separation of the ears (depending on the orientation of the head). For example, a listener may determine a sound is coming from the right because the sound waves reach the right ear first. Interaural level differences occur because the intensity of a sound may change depending on how closer or farther away the sound is from the ears. Softer because they may lose some intensity as they bump and are absorbed by objects they encounter (including parts of the listener's head and body). The head is also primarily responsible for decreasing the intensity of the sound and primarily responsible for ILDs. The sound has to travel through the head to reach the ear farthest from the sound. Both ITDs and ILDs cues are processed in the brain to adequately localize sound (Wightman & Kistler, 1997; Gilkey & Anderson, 1995).

In addition to Duplex theory, researchers have found that there may be more to localization than intensity and time differences. For example, Duplex theory could not
predict why some people were better at localizing sounds correctly than others (Wenzel, Arruda, Kistler & Wightman, 1993). Also, research could not predict why people had trouble differentiating sounds emanating from the front or the back. The role of the ear in localization would further be extended to include the shape and orientation of the ear and how it affects the frequencies in a sound wave.

Head Related Transfer Functions and Localization

Further research would also investigate another dimension of sound that extended the duplex theory of localization. Research noted that the external portion of the ear, known as the pinna, had a special role in the way sounds receive their spatial characteristic (Oldfield & Parker, 1984; Wightman & Kistler, 1997). As acoustical sound waves reach the individual ears, the overall shape, bumps and folds of the ear make small changes in the complexity of the sound (Oldfield & Parker, 1984). Each ear is different and can make subtle changes to sound, more specifically to certain types of sound wave frequencies, which has been shown to be a significant cue for accurate localization (Wightman & Kistler, 1997). This acoustical pattern, specific to each individual (and ear), is referred to as the Head Related Transfer Function (HRTF) and it incorporates changes provided by the pinna as well as ITD and ILD differences (Wightman & Kistler, 1997; Teas, 1994).

The pinna only modifies shorter higher frequencies and makes little change on longer lower frequencies (Wightman & Kistler, 1997). A sound or warning must contain an adequate amount of higher frequency content if HRTFs are going to make a significant impact on the sound’s localizability, without this high frequency information localization performance goes down. This is to say that a sound wave with a lot of high frequency
content will be more localizable because those higher frequencies are the most affected by the HRTFs. Sound localization is in fact poor for sounds below 3,000 Hz, providing more evidence for the role of HRTFs (Tease, 1994). Withington (1999) reports that a warning must contain enough variety in frequency content overall in order for it to be accurately localizable. An example of this would be broadband noise, which is often used in research. Withington's research focused on the problems associated with emergency vehicle sirens. These emergency vehicle sirens do not have enough high frequency content which result in poor localization performance (Withington, 1999). Not only is overall performance affected by frequency content, but certain other localization errors also emerge, which become more apparent with 3D sounds.

**Localization Errors**

Errors in locating sound have been widely documented in literature. Finding the causes and reason behind these errors will aid in better sound technology design, especially with 3D audio displays. Certain errors are especially noticed for certain areas around the head. For example, because the ears are displaced horizontally, persons are better at localizing sounds that come from different directions on the horizon then they are at localizing sounds that come from different elevations, which is primarily due to the subtle changes in the ILDs and ITDs (Tease, 1994). In addition to this, people also have trouble localizing sounds and discriminating between sounds coming from the front and the back of the head or other sounds that are equidistant from the ears (Oldfield & Parker, 1984; Middlebrooks, 1997; Wightman & Kistler, 1997). If 3D sounds and warnings are to be utilized effectively localization errors must be resolved, especially if the warnings contain directionally dependent information such as the location of other airplanes and
traffic. If a pilot mistakes traffic coming from the back as actually coming from the front, the consequence may be life threatening.

The reason behind this confusion lies behind the sound localization cues themselves. Sounds originating from the front and back have very similar ITDs. Once the sound reaches the ear both the right and the left ear make similar adjustment to the sounds (and to the HRTF) that creates further confusion. Oldfield and Parker (1984) also added that due to orientation of the ears, sounds emanating from the back are even harder to localize because they may have the least chance to interact with the bumps and folds of the pinna. That being said the differences may not be enough to overcome the front and back reversal problem. Location confusions have also been seen in other sounds that are positioned equidistant to a particular ear (with similar ITDs and ILDs). Figure 1 illustrates this point. For a given location (front or back), each ear will receive the same HRTF. However, the HRTFs from the two locations are quite similar, especially if you compare them to the HRTFs from both ears when the sound is coming from either the left or the right direction. Depending on the location, frequency content also affects errors in localization for different types of complex sounds.
Figure 1. HRTF Examples per Location. Depending on which direction the sound is emanating from the figures below show what the HRTF would look like for each ear. As you can see from the figures below the HRTFs from the front direction (0 degrees) are very similar to that of the back direction (180 degrees), in comparison to the HRTFs when a sound is emanating from either the left or the right (90 degrees).

(From Ehmann, 2001; Hugh, 2000)
Localization of Speech Targets. The speech spectrum spans from 100 to just over 8000 Hz, and usually does not contain much lower frequency content (Salvendy, 1987). Some research does point that speech targets may do well in comparison to non-verbal warnings. For example, Hass (1998) reported that spatially separated speech warnings were detected and were reacted to just as well, and in some cases better, than non-verbal warnings alone for helicopter environments. The lower frequency content, however, may become problematic for localization performance. Withington (1999) reported that localization errors are in fact highest for frequencies around 3000Hz, which do fall within the speech spectrum, which may be a disadvantage to using speech for 3D auditory warnings.

There has been minimal research comparing the localizability of verbal and non-verbal warnings, however some lessons may be derived from studies using both verbal and non-verbal targets and sounds. Shigeno & Oyama, (1983) did find that listeners are better at localizing vowel sounds than they are at localizing pure tones, which is due to the narrowness in frequency variety of pure tones. Listeners, however, were able to localize broadband/white noise more accurately than vowels or pure tones. In addition to this Gilkey and Anderson (1995) found that listeners in fact made more front/back errors with short words than with broadband noise, adding yet a new problem for 3D auditory warnings. The focus of this study is to see if research on verbal and non-verbal targets will translate to that of verbal and non-verbal cockpit warnings.

Shigeno and Oyama, concluded that complexity (or content) of a sound target ultimately would result in better localization performance. Although verbal sounds have a higher amount of high frequencies, which lend themselves to HRTF adjustments, they
may not be as localizable as sound waves that much have broader frequency content (Withington, 1999; Shigeno & Oyama, 1983). With regards to auditory warnings, accurate localization performance is critical if the message of the warning contains spatial, or directional, information. For example, if an engine on the right side of the aircraft fails, in order for the pilot to react quickly and effectively the warning must emanate from the pilot’s right side.

In addition to errors in localization, other problems and issues arise from the use of 3D sounds and 3D sound technology. Although an in depth look into these issues is beyond the scope of this study, a brief discussion will cover two of the most prevalent problems in sound localization.

Issues with Three-dimensional Warnings and Technology

The relative newness of 3D sound display technology has brought out two main issues for debate: real vs. virtual audio displays and the use of individualized and non-individualized HRTFs.

**Real vs. Virtual Audio Displays**

Three-dimensional sounds are often presented through two different types of displays: Real and Virtual. Real displays resemble much like the normal environment; sounds are projected from their actual locations through the use of many speakers placed from every possible location or one speaker is placed that moves around the listener. Real displays are more realistic, and resemble and mimic the actual environment. Virtual displays present sound from "virtual" or computer simulated locations. Virtual displays accomplish the same by using HRTFs and may be presented through headphones or are
presented by two speakers placed around the listener. For certain environments one type of display may be more useful than the other. If enough resources are available, and the environment is suitable, a real display system could be installed to produce more realistic sounds. However, it may not be feasible to install a large number of speakers in a small and all-ready cramped cockpit, in which case virtual displays may be an option.

Wightman & Kistler (1989) compared both virtual displays to real or "free field" displays and found that localization is comparable. Virtual displays, however, have an increase in front/back errors, which is to say that people on average have greater trouble distinguishing sounds emanating from the front and back regions compared to a real display. It may be that 3D audio software may not be sensitive enough to generate subtle differences between front and back sounds or perhaps there are other cues not explored yet by research. As more research is conducted, better and more sophisticated technology may be developed.

*Individualized vs. Non-individualized HRTFs.*

The pinna is shaped differently for each person and serves an important role in localizing sound accurately. Also, individuals differ on localization abilities as well; some people are just better localizers than others (Begault & Wenzel, 1993). One research issue that has been brought up in localization research is the use of individualized or non-individualized HRTFs. Using individualized functions require that each participant's HRTF be measured, which is often expensive and time consuming. Research often resorts to using a non-individualized HRTF, which involves an "average" HRTF, or one measured by using a manikin head (Wenzel, Arruda, Kistler & Wightman, 1993; Begault & Wenzel, 1993). The use of non-individualized HRTFs has proven to be
a useful tool, if tailor-made functions are not practical. Listeners are able to obtain useful spatial information from sound filtered through non-individualized functions (Wenzel, Arruda, Kistler & Wightman, 1993).

The use of HRTFs by the 3D audio software has great potential for research in sound localization, but the problems of front and back reversal is a nagging problem with no clear solutions. In order to fully utilize 3D sounds, front and back sounds need to be more distinguishable. As mentioned, reacting to ambiguous sound cues and warnings may have dire consequences in flight. Ultimately the problem resides in the similarities between the front and back HRTFs as well as the frequency content of the warnings themselves. Some success has been achieved by adding additional filters that manipulate the frequency content of sound targets, in an effort to make them more localizable to listeners (Ehmann, 2001). Filtering the frequency content must be done with caution; however, as limiting frequency content can also lower the sound's localizability, as seen with the emergency vehicle sirens.

Rationale

The present study extended the research performed by Ehmann (2001). Ehmann (2001) measured the effects of sound cue characteristics on the front and back localization performance for a 3D sound clip. The study utilized 3D audio producing software and non-individualized HRTFs in order to manipulate the frequency content an auditory cue. Filters were used to eliminate either higher or lower frequencies (the cut off utilized was 1000 Hz) from sound cues, which were compared with a "normal" condition where no changes were made to the cues. Results from the Ehmann study indicated that the location of sound did interact with sound filter type but did not significantly decrease
front and back reversals overall (Ehmann, 2001). One interesting finding provided by the Ehmann study was that eliminating lower frequencies did improve localization from sounds emanating from behind the listener. The findings provided by Ehmann's study will be extended by the current study because by using a different more applicable sound stimuli. The sound clip used by Ehmann (2001) was that of a helicopter flying overhead, and although it resembled broadband noise, did not have the applicability that cockpit warning sounds do (no evidence suggests that helicopter noises are relevant sounds heard in the cockpit).

The present study attempted to extend the findings provided by Ehmann (2001) to that of verbal and non-verbal warnings. Previous studies have used broadband, white, pink, or Gaussian noise cues that have been known for their high localizability (Oldfield & Parker, 1984; Wenzel, Arruda, Kistler & Wightman, 1993; Wightman & Kistler, 1997). This study used more applicable sound cues that would normally be heard in a cockpit environment (ex. warning buzzers, verbal instructions) Very few (if any) research has been conducted on their localizability. Previous studies have indicated a high number of front and back errors for both verbal (speech) and non-verbal targets (Begault & Wenzek, 1993; Shinego & Oyama, 1983). Since virtually no research has compared the two types of cues before, directly, this study hypothesized that front and back localization performance differs for both types of stimuli, in fact performance for verbal sound cues should be worse than that of non-verbal cues due to the differences in frequency content (a finding supported by Shinego & Oyama, 1983 and suggested by Stanton & Edworthy 1999).
Frequency content for the sound cues was also manipulated to attenuate certain frequencies. There were three separate conditions that will be used for comparison: high pass, low pass, and normal (which were used by Ehmann as well). The high pass condition only allowed higher frequencies, those frequencies above 1000 Hz, to pass through. This is to say that frequencies above 1000 Hz were heard and the intensity of the frequencies below 1000 Hz was lowered to a level that can barely be heard. The low condition only allowed lower frequencies, those frequencies below 1000 Hz, to pass through and be heard. For this condition, all frequencies below 1000 Hz were heard, and those above 1000 Hz were inaudible. The frequency content in the "normal" condition was not edited and all the frequencies of the sound were heard. This frequency rate was chosen as the cut-off because the software used by Ehmann had pre-made sound filters that utilized 1000 Hz as the cut off mark. Also, 1000 Hz is also the middle frequency for the simple equalizer used by this study.

With regards to frequency filtering, this study expected to show three findings: 1) sounds in the "normal" condition are more localizable then those in the "highpass" or "lowpass" condition; 2) Sound in the "highpass" condition are more localizable than the "lowpass" condition and finally 3) Non-verbal sounds are more localizable than verbal sounds for the "lowpass" condition. Ehmann hypothesized that eliminating certain frequencies may aid in overcoming front and back errors, a hypothesis that was only supported by eliminating frequencies below 1000 Hz (for helicopter sounds) for the back location. Results from this study expected to support hypothesis 1 and 2 because, as mentioned, a warning must contain enough variety in frequency content overall in order for it to be accurately localizable (Withington, 1999), eliminating frequency content.
would degrade localization performance when compared to the normal condition. The sounds in the "highpass" condition were also expected to be more localizable than the "lowpass" condition because high frequencies are affected by the HRTFs more, which is to say that the sounds are more influenced by the bumps and folds of the pinna. Eliminating the lower frequencies will affect the localizability of the sounds negatively by narrowing the range of frequencies available. However, eliminating the high frequencies will have a negative effect on localization, which will especially be shown by hypothesis 3. Presumably, verbal sounds, with more high frequencies will be effected negatively more than their non-verbal counterparts. Salvendy (1987) described that verbal targets generally are composed of high frequencies, which would indicate that eliminating higher frequencies (as in the "lowpass" condition) would drastically impact localization performance negatively.

Finally, this study measured three dependent variables. Participants were scored on how accurately they localize sounds from the front, from the back, and also received an overall accuracy score. In this study front/back localization performance is a dependent variable and was measured for all participants to see if frequency filters may affect specific localization errors. Different frequency content filtering conditions may affect performance in different ways. Examining specific localization performances will expose precise differences in performance that may not be accounted for in a total score. For example, it may be that persons are more accurate at localizing from a specific direction (ex. Front) and may make many localization errors from the opposition location (ex. Back). If the two scores are put together, the scores from the two directions may
average themselves out, and individual localization differences for a particular direction may not be seen.

This study adds to the body of research conducted on sound localization, with specific emphasis on the front and back localization performance. This study hypothesized that there should be interaction between the frequency content condition and that of the type of warning (verbal or non-verbal), because both types of warnings have different ranges of frequency content. Because no previous research has been conducted comparing the localizability of verbal warnings and non-verbal warnings this study expected to show difference between the two, and it is anticipated that the differences in localization would be affected by frequency filtering and would result in poorer localization when compared to the normal condition. This may be due to the fact that limiting and narrowing frequency content leads to poor localization performance, a phenomena that has been previously observed with emergency vehicle sirens (Withington, 1999).
METHODS

Participants

Ten participants were recruited from the undergraduate population at Embry-Riddle Aeronautical University. Nine participants were undergraduate students and one participant was a graduate student. Nine participants received extra credit for participation in this experiment from their course instructors. Five participants were female and five were male with mean age of 21 ($SD = 2.9$). Eight participants reported that they had normal hearing while two participants reported having very good hearing. No participants reported any previous hearing or auditory trauma. The decision to use such a small number of participants was made based on the fact that previous experiments have been able to show significant results using similarly small groups. Previous studies had used anywhere from four participants to sixteen, although this may have been due to the availability of participants or time constraints.

Materials

Three separate software programs were used to create and present the 3D sound cues. In order to give sound cues their spatial aspect a software package titled "Maven 3D, trial version 1.2" by Emersys was used. Maven3D is a digital sound-editing program that can give a sound a 3D quality through the use of non-individualized HRTFs. A demonstration version was used and the sounds were recorded using Microsoft Sound Recorder version 5.1 (Maven3d.com, n.d.).

Sounds were edited so that they would appear to come from the front, back, left, and right, orthogonal to the head orientation of the person along the horizontal axis. The
individual sound's frequency content was then manipulated using Blaze Audio Wave Creator 3, by Singing Electrons, Inc. Using the program's equalizer; certain frequencies were minimized and almost muted to suit the experiment conditions (Blaze Audio, Inc., n.d.). Sounds were also adjusted for different loudness or intensity levels.

These programs were used on a Dell Inspiron 1000 laptop PC utilizing an Intel Celeron processor, and a Windows XP platform. This PC contained a SoundMAX audio card to present. The sounds were played for the user through a pair of Philips stereo headphones that covered the pinna. Conventional cockpit warnings were used. The sounds utilized were that of the collision with terrain warning (verbal) and autopilot disconnect warning (non-verbal). Each sound was approximately 2 seconds long and were both found on the Internet (Planecrashinfo.com, n.d.).

The responses from each participant were entered into an Excel spreadsheet and analyzed using SPSS software.

**Design**

This study was a 2 x 3 complete within subjects design (Auditory warning type: verbal versus non-verbal and frequency content at three levels: highpass filtering, lowpass filtering and normal). The conditions are listed below in Table 2. A within subjects design was chosen because it was felt that hearing both verbal and non-verbal warnings at the same time would not interfere with the localizability of the sounds.

**Procedure**

Participants were initially briefed that their localization abilities would be measured. The participants were blindfolded, so that no visual cues would bias their
responses, and were instructed to respond verbally with their perception of where the sound was coming from when they hear the appropriate sound cue. The participants were only allowed to respond “Front,” “Back,” “Left,” or “Right,” and were encouraged not to guess but provide an answer they were most sure of.

Table 2. Experimental Design. For each experimental condition Front, Back and Total localization performance score is measured.

<table>
<thead>
<tr>
<th></th>
<th>Highpass</th>
<th>Normal</th>
<th>Lowpass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal Warning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-verbal Warning</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Participants were seated in a quiet room facing the experimenter and heard the sound through the Philips headphones. Warning sounds that were sampled were approximately 2 seconds long and were followed by a brief pause to allow the participants to answer. For each condition the participant listened to 25 sounds, for a total of 150 sounds (For each condition 10 sounds were from the front, ten from the back, and five from either the left or the right). Each participant received their own randomized playlist. Left and right sounds were played to provide a manipulation check for participant guessing. Responses for these sounds were noted but not included as part of the total localization score. Total performance was recorded and analyzed as well as individual performance for both front and back locations. This was done to examine whether or not specific localization differences occurred due to differences in location.
RESULTS

Localization performance was analyzed by computing the total amount of correct direction responses for each combination of the six experimental conditions. For each condition the highest score achievable was a score of 20 (10 responses from the front and 10 from the back location). Table 3 depicts the means and standard deviations for each experimental condition. Table 4 breaks down the individual responses by the type of errors made. For example, the amount of times front and back reversals were made is listed as well as the amount of times either left or right was given as a response for a front or back sound.

Table 3. Average localization scores per experimental condition for N=10.

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Lowpass</th>
<th>Normal</th>
<th>Highpass</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M$</td>
<td>$SD$</td>
<td>$M$</td>
<td>$SD$</td>
</tr>
<tr>
<td>Warning Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verbal</td>
<td>15.40</td>
<td>3.72</td>
<td>14.7</td>
<td>3.02</td>
</tr>
<tr>
<td></td>
<td>14.70</td>
<td>2.95</td>
<td>14.93</td>
<td>3.15</td>
</tr>
<tr>
<td>Non-Verbal</td>
<td>10.90</td>
<td>4.04</td>
<td>7.60</td>
<td>4.43</td>
</tr>
<tr>
<td></td>
<td>10.50</td>
<td>3.87</td>
<td>9.67</td>
<td>4.24</td>
</tr>
<tr>
<td>Total</td>
<td>13.15</td>
<td>4.43</td>
<td>11.15</td>
<td>5.05</td>
</tr>
<tr>
<td></td>
<td>12.60</td>
<td>3.87</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4. Localization Responses Breakdown. This table breaks all the responses down by the types of errors made. The left column indicates the correct response and the number indicates how many times the particular incorrect response was given.

<table>
<thead>
<tr>
<th>Incorrect Responses</th>
<th>Correct Responses</th>
<th>Total Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>x</td>
<td>193</td>
</tr>
<tr>
<td>Back</td>
<td>138</td>
<td>x</td>
</tr>
<tr>
<td>Right</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Left</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>138</td>
<td>198</td>
</tr>
</tbody>
</table>

A repeated measures ANOVA was performed on the total number of correct localization responses. Results indicated that there was a significant difference amongst warning type conditions such that the verbal warning localization was correctly located more often than the non-verbal warning cases, $F (1, 9) = 19.99, p < .05$. Results indicated that there was no significant difference amongst filter condition, $F (2, 18) = 2.46, p > .05$. Results also indicated no interaction between warning type and frequency filter, $F (2, 18) = 1.82, p > .05$. Figure 2 presents a graphical representation of the means for each condition, and it can be clearly seen that no interaction existed between frequency filter condition and localization performance for verbal and non-verbal cockpit warnings.
Table 5. Analysis of variance for total correct response.

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>Df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
<th>Eta Squared</th>
<th>Observed Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warning Type</td>
<td>416.067</td>
<td>1</td>
<td>416.067</td>
<td>19.996</td>
<td>0.002</td>
<td>0.690</td>
<td>0.970</td>
</tr>
<tr>
<td>Error</td>
<td>187.267</td>
<td>9</td>
<td>20.807</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency Filter</td>
<td>42.700</td>
<td>2</td>
<td>21.350</td>
<td>2.464</td>
<td>0.113</td>
<td>0.215</td>
<td>0.431</td>
</tr>
<tr>
<td>Error</td>
<td>155.967</td>
<td>18</td>
<td>8.665</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warning Type* Frequency Filter</td>
<td>25.433</td>
<td>2</td>
<td>12.717</td>
<td>1.828</td>
<td>0.189</td>
<td>0.169</td>
<td>0.331</td>
</tr>
<tr>
<td>Error</td>
<td>125.233</td>
<td>18</td>
<td>6.957</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For $\alpha = .05$

Figure 2. Localization Performance of Verbal and Non-Verbal Cockpit Warnings.

A repeated measures ANOVA was also conducted on the front and back warning presentation location subsets of the data to see if the effects would change with respect to different locations. Due to the nature of the Front/Back reversal errors seen in the past
literature, it was felt that location may produce differences when it came to different locations (i.e. front and back). Separate front and back analysis may show different effects that may not be seen at the global analysis. For example, for any experimental condition, the response score may be attributed to a large amount of correct front responses; where in another condition the opposite may be true. Ehmann (2001) had previously used location as an independent variable but found no differences between front and back localization performance. An ANOVA test may show if his findings translated to cockpit warnings.

**Front Localization Performance**

A repeated measures ANOVA was conducted to determine if warning type had an effect on the number of correct location responses for the front location. The highest possible score achievable for each experimental condition was 10 correct responses. Table 6 depicts the averages and standard deviations for correct identification of stimuli presented from the front location.
Table 7. Analysis of variance for total correct response for the front location.

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P</th>
<th>Partial Eta Squared</th>
<th>Observed Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warning Type</td>
<td>331.350</td>
<td>1</td>
<td>331.350</td>
<td>47.474</td>
<td>0.000</td>
<td>0.841</td>
<td>1.000</td>
</tr>
<tr>
<td>Error</td>
<td>62.817</td>
<td>9</td>
<td>6.980</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency Filter</td>
<td>2.700</td>
<td>2</td>
<td>1.350</td>
<td>0.380</td>
<td>0.689</td>
<td>0.041</td>
<td>0.102</td>
</tr>
<tr>
<td>Error</td>
<td>63.967</td>
<td>18</td>
<td>3.554</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warning Type&lt;sup&gt;2&lt;/sup&gt;</td>
<td>39.700</td>
<td>2</td>
<td>19.850</td>
<td>4.487</td>
<td>0.026</td>
<td>0.333</td>
<td>0.692</td>
</tr>
<tr>
<td>Frequency Filter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>79.63</td>
<td>18</td>
<td>4.424</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For $\alpha = .05$

Figure 3. Localization Performance of Verbal and Non-Verbal Cockpit Warnings for the Front location.

*Back Localization Performance*

A repeated measures ANOVA was conducted to determine if warning type had an effect on the number of correct location responses for the back location. The highest
possible score achievable for each experimental condition was 10 correct responses.

Table 8 depicts the averages and standard deviations for the front location.

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Lowpass</th>
<th>Normal</th>
<th>Highpass</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Warning Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verbal</td>
<td>8.90</td>
<td>0.88</td>
<td>6.00</td>
<td>2.62</td>
</tr>
<tr>
<td>Non-Verbal</td>
<td>8.40</td>
<td>1.96</td>
<td>5.40</td>
<td>2.37</td>
</tr>
<tr>
<td>Total</td>
<td>8.65</td>
<td>1.49</td>
<td>5.70</td>
<td>2.45</td>
</tr>
</tbody>
</table>

Results indicated that there was no significant difference amongst warning type conditions indicating that verbal and non-verbal warnings are similarly localizable, $F(1, 9) = 3.85, p > .05$, nor was any interaction between warning type and frequency filter, $F(2,18) = 2.88, p > .05$. Results indicated, however, that there was a significant difference amongst filter condition for the back location indicating that filtering improved localization of back presentation for both highpass and lowpass conditions compared to the normal condition, $F(2, 18) = 10.124, p < .05$. Table 9 provides the repeated measures source table information and Figure 4 shows a graphical depiction for the results.
Table 9. Analysis of variance for total correct response for the back location.

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P</th>
<th>Partial Eta Squared</th>
<th>Observed Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warning Type</td>
<td>2.017</td>
<td>1</td>
<td>2.017</td>
<td>0.385</td>
<td>0.550</td>
<td>0.041</td>
<td>0.086</td>
</tr>
<tr>
<td>Error</td>
<td>47.150</td>
<td>9</td>
<td>5.239</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency Filter</td>
<td>90.700</td>
<td>2</td>
<td>45.350</td>
<td>10.124</td>
<td>0.001</td>
<td>0.529</td>
<td>0.967</td>
</tr>
<tr>
<td>Error</td>
<td>80.633</td>
<td>18</td>
<td>4.480</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warning Type * Frequency Filter</td>
<td>1.033</td>
<td>2</td>
<td>0.517</td>
<td>0.288</td>
<td>0.753</td>
<td>0.031</td>
<td>0.089</td>
</tr>
<tr>
<td>Error</td>
<td>32.30</td>
<td>18</td>
<td>1.794</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For \( \alpha = .05 \)

Figure 4. Localization Performance of Verbal and Non-Verbal Cockpit Warnings for the back location.
Auditory warnings are important for operating an aircraft safely. There is no doubt that their inclusion has boosted safety for the pilot and passengers (Wickens, 2003). However, the design of these warnings has changed little over the years and many problems have been associated with them. Current warnings are omni-directional, or cannot be perceived as coming from any particular direction. New software is able to adjust the frequencies of the omni-directional warning sounds so that when heard, a person perceives them as coming from directions other than that of where physical sound presentation is located. The applications of this emerging technology have not yet fully been developed, and adding spatial qualities to cockpit warnings may be an option towards improving them. However, certain drawbacks have been observed using these applications. The limited research available has shown that listeners have been observed to have poor localization performance for the front and back regions about the head, a fact that needs to be explored further by research (Oldfield & Parker, 1984; Middlebrooks, 1997; Wightman & Kistler, 1997).

In order for 3D audio technology to be fully applicable to modern cockpits, it is important that front and back localization errors be minimized and explained. Mistakes made in localizing sounds representing traffic or dangerous circumstances could lead to fatality or catastrophic loss. Ehmann (2001) utilize specialized "filters" that alter the frequency content of sounds in an attempt order to improve front/back sound localization. Ehmann's study met with marginal results and only slight improvements for localization of sounds emanating from the back region.
The purpose of this study was to extend the research conducted by Ehmann (2001) to include auditory warnings that would be found in an airplane cockpit. This was conducted in order to establish frequency content as an important characteristic for the design of 3D cockpit warnings. The experiment also aimed to compare the localization performance of both verbal and non-verbal cockpit warnings. Three frequency filter conditions were established: lowpass, highpass and normal. Frequency content was edited by minimizing a range of frequencies based around a boundary of 1000 Hz. For the lowpass condition, only frequencies below 1000 Hz were heard by the participants. With the highpass condition, only frequencies above 1000 Hz were heard by the participants and all frequencies were heard for the normal condition. The cockpit warnings heard were that of the autopilot disconnect warning (non-verbal warning) and that of the close proximity to terrain warning (verbal warning). Results for warning type showed some differences at the global level, when all factors were included, as well as when localization performance for individual locations was further explored.

Global Analysis:

This study supports previous findings by Wightman & Kistler (1997) that front/back localization errors do occur with virtual auditory displays. Results indicated at the global level that verbal warnings were more localizable than non-verbal, which failed to support the first hypothesis. This difference may have been attributed to how people are used to hearing speech or verbal information. When a person first hears either a word or another person speaking we are automatically adjust our position to face the source so we could hear it better. This may lead us to associate the front with words and other verbal messages.
This finding, however, appears to be contrary to the Shinego and Oyama (1983) study which found that non-verbal sounds were more localizable than verbal sounds. The disparity may be due to differences in sound stimuli. Shinego and Oyama (1983) had used one syllable shorter sounds whereas the sounds used in this study was a two syllable word (Terrain). Future research may want to explore the effect of word length on localization.

No effect was found for the frequency manipulation in the global analysis. This may suggest that the frequency filter may not have been strong enough to support differences, as indicated by the low power of the test (.431). Although previous research had indicated that the use of a small sample size could yield significant effects, this study suggests that, at least for frequency differences, a larger sample size may be required to find differences that may exist.

At the global level, it appears the only differences found were between verbal and non-verbal cockpit warnings. Since no previous research had attempted to compare the two warning types against each other this study may suggest that verbal warnings are more localizable than non-verbal warnings. The results from this study further indicate that there may be no interaction between warning type and frequency filter, however the use of a larger sample may strengthen the theory.

Since Ehmann found that filtering the profile of the stimuli did impact localization of information presented in the back location, ANOVA tests were conducted to see if the errors may have been attributed to differences in location. These tests were conducted in order to determine if the localization performance was due to a majority of errors made for either the front or the back or if the errors were similar for both locations. Location
had previous been examined by Ehmann (2001) and improvements in performance were found for the back location under lowpass filtering. The tests in this study however, did show that when measuring location differences did exist with amongst the two types of warnings. The subtle differences were not seen at the global level but may be due to the natural differences involved in hearing both sounds emanating from the front and back location which may contribute to the front/back reversal problem.

*Front Localization*

Results from the ANOVA on the warning presented from the front location showed that verbal and non verbal warnings exhibited differences such that verbal warnings were more localizable than non-verbal warnings. The effect in the front presentation mirrored the global analysis for cockpit warnings. As mentioned experience with hearing speech and verbal information and associating it with the front location may explain the similarities in performance.

Frequency filter conditions did not appear to exhibit differences for the front location. However, there did appear to be an interaction between frequency filter and type of warnings. For the frequency filter cue, the filtering itself may not have been strong enough to produce a desired effect, as seen by the relatively low power (.10). Use of a higher number of participants may produce desired significant interaction effects. On the other hand, the low effect size may suggest that the frequency filter may not be an important issue when it comes to localizing sounds from the front.
Back Localization

Results from the ANOVA test showed no differences attributed to warning type for conditions. The lack of significance may be due to the relatively low power of the test (.08) may suggest that future research may make alterations, such as the use of more participants, in order to find significant differences.

Interestingly enough frequency filtering did exhibit significant differences for these data. For the back location, it may seem that the role of frequency content may play a role in how sounds from the back are localized. An etα² of .52 indicates that about half of the variability in this test can be attributed to frequency filter. It appears that those experiment combinations with either highpass or lowpass frequency filter were more localizable than the normal condition. These results partially support Ehmann (2001) who had also found improvements in back localization for the lowpass condition. As seen in Figure 1, HRTFs for the back location are very similar. The use of a frequency filter may actually provide an additional cue to make the HRTFs distinguishable enough to produce correct localization responses. Subtracting a certain range of frequencies for the warnings may not have degraded performance by excluding valuable cues, but instead may have created a new cue that would help participants clear up some confusion attributed to the similar HRTFs. Since participants are used to hearing clear undistorted sounds from the front location, the addition of a frequency filter may have lead participants to judge that the sounds were actually coming from the back.

Overall, the results from this study do pose an interesting question about the front/back reversal problems for virtual displays. It appears that more errors are made in front location than for the back. Participant made around 4-5 localization errors for the
front location, where as participants made 2-3 errors as seen in figures 3 and 4. It appears that frequency filtering may play a more prominent role in improving performance for the back location than the front. This study does suggest that other variables may contribute to localization performance for front location that may have de-emphasized the frequency cue. It is unclear why differences seen for different location were not also seen at the global analysis. However, it may be that the lack of differences may be in part do to the orientation of the ears and how sounds emanating from the back location must travel through the pinna (and the back of the head) to reach the ear. On the other hand, filtering may have affected the back localization but did not affect the front location as much, so that when those data are bundled together the differences in performance are averaged out.

One important finding that can be gathered from the study is the differences gathered by measuring different types of warnings. No previous research had ever attempted to compare verbal and non verbal cockpit warnings before. As mentioned, significant differences did occur between the two types of warnings used here but those differences were not seen for the back location. The role of frequency content may still be up for debate and it is up to future research to develop the topic further and explain why frequency content is important for localizing the back but not so much for the front. This study also brought some interesting questions that may be further addressed by future research.

*Future Research*

Although some interesting findings were seen by this study, more sophisticated equipment could have brought about more significant findings for certain variables. The
software used for this experiment was a trial version utilized 1000 Hz as a cut off for the frequency filter conditions, a more comprehensive cut off point for different frequency conditions. Although this cut off proved to yield differences for the back location it did not yield differences at the global level or for the front location. This cut off may have been too low and may not have taken into account the total range of frequencies that could be heard. Including a broader range in frequencies sounds may become more localizable as they become more distinct.

The results from this study point out that other variables may exist that contribute to the differences in sound localization performance that may not have come up in the course of developing this study. One such issue is that of time and change of frequencies. Research in complex sounds, such as warnings, is difficult to generalize across many different types of sounds because the frequencies of the warnings themselves do not remain constant in intensity over the duration of the sound. For example with verbal warnings, the different frequencies may change as each word and syllable is pronounced. With non-verbal warnings different undulations and changes in tone also exhibit changes in the frequencies. This factor may explain why this study did not support findings by Shinego and Oyama (1983). Their study compared one syllable short verbal and non-verbal sounds where as this study compared one autopilot disconnect warning and a two syllable word (terrain). Shinego and Oyama (1983) found that non-verbal sounds were more localizable, where as the opposite was supported in this study. Although the sounds used in this study were matched according to loudness, changes in particular frequency intensities for a specific time interval could not be matched across sounds. Future
research may want to explore the changes in frequencies over the duration of the sound to see if those differences may affect sound localization.

The question is left now to future researchers and designers of 3D cockpit warnings. There still appears to be some question as to whether or not frequency filtering may become a factor for resolving front and back localization confusions. The role of frequency filters may be different for front and back warning sounds, and more research is needed to develop and explain the reasoning why there are such differences. Although frequency filters appear to improve performance for the back location, further methods may need to be developed to improve localization warnings emanating from the front.
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