ACQUISITION, RESPONSE, AND ERROR RATES WITH THREE SUITES OF COLLISION WARNING SOUNDS

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Summary: The acquisition, response speed, and error rates of three suites of collision warning sounds were investigated to evaluate the effect of sound alteration on responding. In each suite, four sounds were pictorially associated with four collision scenarios. Suite A included two natural sounds, and two artificial sounds semantically associated with one of four crash scenarios; Suite B was a variant of A, altered to reduce perceived urgency; Suite C was a set of abstract sounds constructed to vary in urgency and matched to the subjective urgency of each scenario. For each suite, subjects first learned to associate the suite's warning sounds with an assigned crash scenario to an established criterion. This was followed by reaction time trials in which a sound was played and subjects quickly identified the scenario associated with the sound. For both young and old subjects, Suite A produced the shortest reaction times and fewest trials to criterion, suggestive of the response efficiencies reported for auditory icons. In contrast, the sounds used in Suite B, while variants of Suite A, were most difficult to learn and were not different from Suite C with respect to error rates and reaction time. It is suggested that even relatively minor alterations of a warning sound can result in marked differences in acquisition and performance.

INTRODUCTION

Auditory warnings are a particularly useful means to signal an imminent collision. There are few other ways to inform a driver quickly—and without involving a redirection of gaze—that an immediate response is urgently needed. In efforts to communicate an appropriate degree of urgency several acoustic properties of sounds have been found to be associated with urgency (Edworthy, Loxley, & Dennis, 1991; Hellier, Edworthy, & Dennis, 1993). These include frequency, pulse rate and duration, onset time, and volume. However, other attributes besides urgency are also associated with warnings, including annoyance, and these can also affect the suitability of a sound as a collision warning. While annoyance is often correlated with urgency (Tan & Lerner, 1995), annoyance may also be influenced by non-acoustic factors like perceived alarm appropriateness (e.g., Marshall, Lee, & Austria, 2007). Other factors, related to semantic associations and prior learning, may also influence how a warning sound is perceived and responded to (Petocz, Keller, & Stevens, 2008). Such factors may be responsible for the observed advantages in the use of auditory icons as warnings (Belz, Robinson, & Casali, 1999; Graham, 1999; Stephan, Smith, Martin, Parker, & McAnally, 2006). The following study investigates if a set of sounds with strong semantic associations (Suite A) can be digitally altered in some acoustic characteristics associated with urgency (Suite B), without compromising response efficiency. A baseline set of abstract warning sounds (Suite C) is also used for comparison.

METHOD

Participants

Twenty-four individuals participated in this study, partitioned into four groups based on age–young (ages 18 to 28) and older (ages 62 to 81)–and gender. All subjects were given an audiometric screening for hearing loss outside of age-related norms. There were six subjects in each group.

Stimulus Construction

The warning sounds were developed in the context of the NHTSA's Integrated Vehicle Based Safety System (IVBSS) project in which four different collision warning technologies are integrated into a single vehicle. One issue examined in this project was the practicality of associating a different auditory warning with each collision warning. If separate warnings are desirable, it is important that they be easy to learn, easily distinguishable from each other, and elicit a rapid and appropriate response.

Three sound suites were constructed containing four warnings associated with each of four IVBSS scenarios: forward-collision warning (FCW), curve speed warning (CSW), lane change-merge (LCM) warning, and lateral drift warning (LDW). The three suites are described in Table 1.

Table 1. Types of warning sounds

Suite	Warning Scenario			
	FCW	**LCM**	**CSW**	**LDW**
A (semantic)	Appliance beep	Horn honk	Squealing tires	Rumble strip
B (less urgent A)	Appliance beep	Horn honk	Squealing tires	Rumble strip
C (abstract)	High Urgency	(Med-High)	(Med-Low)	(Low Urgency)

Suite A was developed to exploit semantic relationships between the target crash scenario and the sound. For example, the LCM warning used a synthesized honking horn that mimicked the kind of response one might receive from another driver if one encroached into that driver's lane; the CSW warning used the sound of squealing tires to mimic the sound of excessive speed on a curve; the LDW warning contained low and high frequency pulsing resembling a rumble strip sound; the FCW warning, although abstract, arguably resembled the kind of urgent alarm generated by common appliances (e.g., clock radios, microwave ovens). Suite B was constructed from the basic sounds used in Suite A, but modified to reduce perceived urgency. For example, the pitch of the FCW appliance beep was dropped (1500 Hz to 1100 Hz), the pulse interval was increased (100 ms to 200 ms), the pulse duration was increased (70 ms to 160 ms), and so forth. The complete list of modifications is shown in Table 2.

Table 2. Modifications of auditory icons

Warning	Attribute	Suites	
		A	B
FCW (appliance beep)	Pitch (f_0)	1500 Hz	1100 Hz
	Pulse rate	100 ms	200 ms
	Duration	70 ms	160 ms
	Onset	5 ms	40 ms
	Pulses	7	3
LCM (horn-honk)	Pitch (f_0)	1000 Hz	800 Hz
	Pulse rate	160 ms	250 ms
	Duration	150 ms	250 ms
CSW (tire squeal)	Duration	600 ms	300 ms
	Sample playback speed	100 %	94 %
	Onset	30 ms	50 ms
LDW (rumble strip)	Pitch (f_0)	400 Hz	450 Hz
	Pulse rate	150 ms	200 ms
	Duration	50 ms	120 ms
	Onset	10 ms	50 ms

Suite C was developed using abstract sounds of differing urgency based on a prior investigation which modeled urgency ratings to acoustic characteristics (Green et al., 2008). Estimated perceived urgency ratings were generated from all acoustic parameter combinations using coefficients of the fitted model. The four stimuli used in Suite C included the most and least urgent sounds, as well as two sounds equidistant from each other and the neighboring extremes. This is shown in Table 3 along with the projected urgency ratings.

Table 3. Characteristics of the abstract warning sounds for the suite C set of warnings

Projected Urgency Rating	Sound Characteristics							
	Wave Type	Har-monic	Pitch (Hz.)	Speed (ms)	Onset (ms)	Pulses	Pitch Var.	Rhythmic Var.
7.7 (FCW)	Sq	Yes	1400	140	0	5	No	No
6.3 (LCM)	Sine	Yes	1000	80	20	7	No	Yes
5.0 (CSW)	Sq	No	500	110	10	5	Yes	No
3.7 (LDW)	Sq	No	500	110	20	3	Yes	Yes

All sounds were presented through a set of stereo headphones calibrated for loudness with a sound pressure meter. All sounds were presented in the center radial direction at 80 dBA; a stereo recording of road noise was mixed with the warning stimulus and presented at 70 dBA throughout the session.

Procedure

A four-choice reaction-time method was used in which participants were asked to press one of four keyboard keys associated with one of four sounds within a block of trials. The three sound suites were blocked and presentation order was counterbalanced to offset order effects (as shown in Table 4). A block began with an initial presentation of each warning sound in the suite, accompanied by a diagram of the crash scenario associated with the sound and an identification of which key to press when the sound is presented in later trials. The mapping between response key and scenario was fixed across all blocks. Scenario diagrams are shown in Figure 1. This training sequence was repeated once.

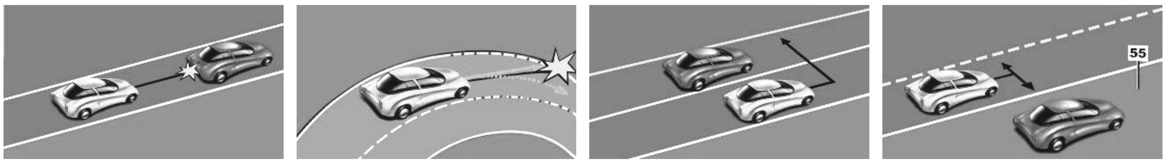

Figure 1. Scenario diagrams.

Following the initial presentation of sounds and their associated scenarios and response keys, subjects were given a series of acquisition trials in which a sound was presented for response. Acquisition continued until a criterion of eight consecutive correct responses were made. Response times greater than three seconds were counted as errors. The number of trials taken to reach this criterion provided a basic measure of learning ease. Once the learning criterion was reached, subjects continued with 40 additional reaction-time trials, ten repetitions of each of the four sounds within each block of sound suites. Reaction time was recorded for each response, and responses averaged within suites, excluding error trials.

Table 4. Experimental design.
(The order of suite presentation was counterbalanced across subjects.)

Sound Suite	Test Phase	Notes
Suite A	Practice	Present FCW, CSW, LCM, and LDW sounds until subject produces eight errorless trials in a row.
	Test	Collect reaction time to randomly-presented FCW, CSW, LCM, and LDW sounds. Two repetitions of each sound within each block.
Suite B	Practice	Same procedure as Suite A.
	Test	Same procedure as Suite A.
Suite C	Practice	Same procedure as Suite A.
	Test	Same procedure as Suite A.

RESULTS

Trials to Criterion

A mixed-model analysis of variance (modeling subject as a random factor) of trials to reach criterion—8 consecutive correct responses—found a main effect of age group and sound suite on trials to criterion. Younger subjects learned to associate the responses to the sounds more quickly than older subjects. On average, they reached the criterion of eight consecutive errorless trials after 19 trials while older subjects required 77 trials ($F(1,22) = 18.74$, $p < 0.01$). Subjects also reached criterion earlier with Suite A than with the others ($F(2,43) = 5.93$, $p < 0.01$). There was also an interaction between age and sound suite: older subjects learned Suite A in fewer trials than either Suites B and C, while younger subjects learned both Suite A and C more quickly than Suite B ($F(2,43) = 3.79$, $p < 0.05$). These effects are shown in Figure 2.

A main effect of block order was also observed ($F(1,43) = 6.51$, $p < 0.05$). Subjects reached criterion in fewer trials in each consecutive block (64, 54, and 27 trials in the first, second, and third blocks, respectively).

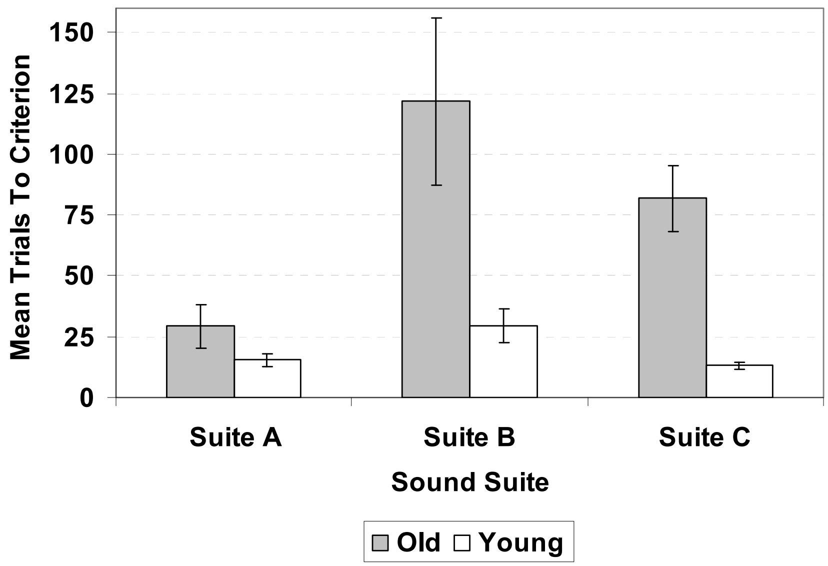

Figure 2. Mean and standard error (SE) of trials to criterion for older and younger participants

Error Rate

Overall, judgment errors were made on 15 percent of the trials. Older subjects made, on average, seven more errors than younger subjects (23 versus 6 percent of 40 trials; $F(1,22) = 33.86$, $p < 0.01$). Error rate also declined over blocks ($F(1, 43) = 9.84$, $p < 0.01$). Average error rates were 19 percent on the initial trial block, 13 percent on the second, and 11 percent on the third. No effect of sound suite on error rate was observed, nor was any interaction found between factors. Error rates are shown in Figure 3.

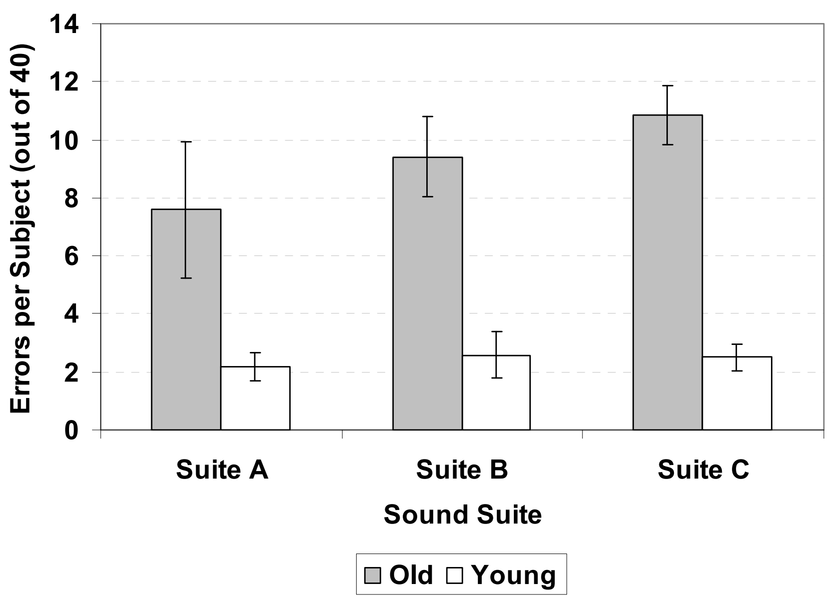

Figure 3. Mean and SE of errors by suite for older and younger participants

Choice Reaction Time

Trials in which a response error occurred were excluded from the reaction time analysis. An analysis of variance revealed main effects of age group ($F(1,22) = 11.79$, $p < 0.01$) sound suite ($F(2,45) = 5.24$, $p < 0.01$), and block order ($F(1,45) = 4.77$, $p < 0.05$). In general, the mean reaction time in older subjects was about 300 ms longer than in younger subjects (see Figure 4). Reaction times for Suite A sounds were about 150 ms faster than for Suite B, and 130 ms faster than for Suite C.

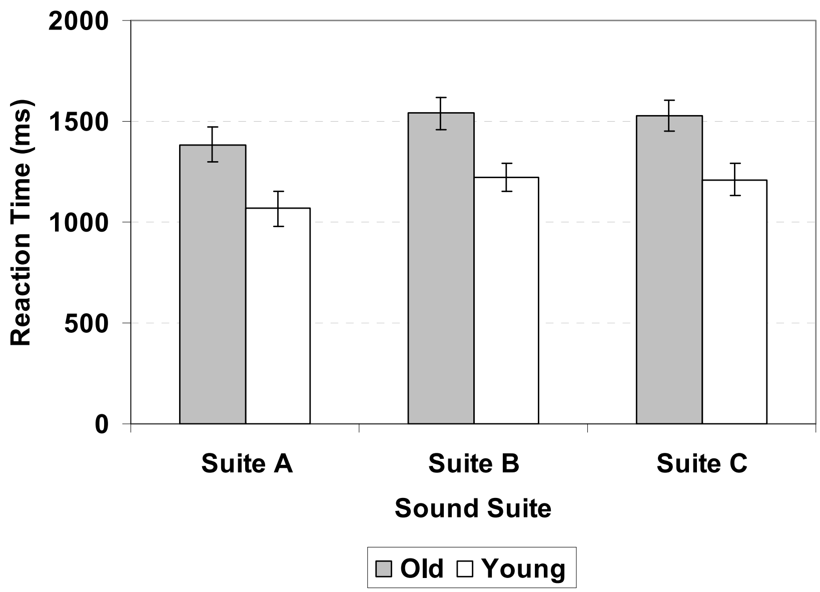

Figure 4. Mean reaction times and SE for responding within each sound suite.

CONCLUSIONS

The sounds used in Suite A produced substantially fewer acquisition trials and substantially shorter reaction times, suggesting that semantic associations between sounds and crash scenarios can result in substantially better performance than arbitrary sounds matched to crash scenarios by urgency as in Suite C. It is also clear that even minor alterations to warning sounds can dramatically alter a participant's performance. It is possible that with such alteration, the resulting Suite B sounds no longer retained the same semantic associations that their Suite A counterparts held. For example, the altered horn-honk sound in Suite B may not have been as easily associated with an automobile horn as its Suite A counterpart. However, side-by-side, the two sounds bear an unmistakable resemblance to each other. It is also possible that the altered sounds may have evoked other semantic associations in the listener that may have interfered with associations to the crash scenarios.

The results suggest that attempts to hybridize warning sounds by blending the semantic associations of natural sounds with current understanding of acoustic characteristics of sounds that govern urgency or annoyance may not easily produce an effective warning.

ACKNOWLEDGMENTS

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REFERENCES

Belz, S. M., Robinson, G. S., & Casali, J. G. (1999). A new class of auditory warning signals for complex systems: auditory icons. *Human Factors, 41*(4), 608-618.

Edworthy, J., Loxley, S., & Dennis, I. (1991). Improving auditory warning design - relationship between warning sound parameters and perceived urgency. *Human Factors, 33*(2), 205-231.

Graham, R. (1999). Use of auditory icons as emergency warnings: evaluation within a vehicle collision avoidance application. *Ergonomics, 42*(9), 1233-1248.

Green, P. A., Sullivan, J. M., Tsimhoni, O., Oberholtzer, J., Buonarosa, M. L., Devonshire, J., et al. (2008). *Integrated vehicle-based safety systems (IVBSS): human factors and driver-vehicle interface (DVI).* (Technical Report No. UMTRI-2007-43). Ann Arbor: The University of Michigan Transportation Research Institute.

Hellier, E., Edworthy, J., & Dennis, I. (1993). Improving auditory warning design - quantifying and predicting the effects of different warning parameters on perceived urgency. *Human Factors, 35*(4), 693-706.

Marshall, D. C., Lee, J. D., & Austria, P. A. (2007). Alerts for in-vehicle information systems: annoyance, urgency, and appropriateness. *Human Factors, 49*(1), 145-157.

Petocz, A., Keller, P. E., & Stevens, C. J. (2008). Auditory warnings, signal-referent relations, and natural indicators: re-thinking theory and application. *Journal of Experimental Psychology-Applied, 14*(2), 165-178.

Stephan, K. L., Smith, S. E., Martin, R. L., Parker, S. P. A., & McAnally, K. I. (2006). Learning and retention of associations between auditory icons and denotative referents: Implications for the design of auditory warnings. *Human Factors, 48*(2), 288-299.

Tan, A. K., & Lerner, N. D. (1995). *Multiple attribute evaluation of auditory warning signals for in-vehicle crash avoidance warning systems.* (Technical Report No. DOT HS 808 535). Washington, DC: National Highway Traffic Safety Administration.